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REACCELERATION OF ION BEAMS FOR PARTICLE THERAPY

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Abstract

At the Heidelberg Ion-Beam Therapy Centre (HIT) more than 2000 cancer patients have been treated with ions using the raster-scanning method since 2009. The synchrotron provides pencil beams in therapy quality for more than 250 energy steps for each ion species allowing to vary the penetration depth and thus to irradiate the tumour slice-by-slice. So far, changing the beam energy necessitates a new synchrotron cycle, including all phases without beam extraction.

As the number of ions that can be accelerated in the synchrotron usually exceeds the required number of ions for one energy slice, the duty cycle could be significantly reduced by reaccelerating or decelerating the remaining ions to the adjacent energy level. By alternating acceleration and extraction phases several slices could be irradiated with only short interruptions. This leads to a better duty cycle and a larger number of patients that can be treated in the same time.

Therefore the behaviour of a reaccelerated but transversally blown up beam - due to the use of RF-knockout extraction - must be investigated in detail, beam losses have to be minimised. To estimate the potential benefit of such an operation mode, treatment time has been simulated and compared to the time achieved in the past. A reduction of more than 50 % is possible!

INTRODUCTION

Tumour therapy with carbon ions and protons has been carried out at the Heidelberg Ion Therapy-Centre (HIT) since 2009. Up to now, more than 2000 patients have been treated, approximately 50 - 60 patients are treated every day.

Rasterscan Technology

All patients at HIT are treated using the rasterscan technology [1], see Fig. 1. This method allows very high dose conformity to target volume as the beam is actively controlled in longitudinal and lateral direction.

In the irradiation planning the tumour is subdivided in slices of equal ion energy, which corresponds to the ion penetration depth. Two scanner magnets guide the mono-energetic pencil beam along a predefined pattern to deliver an individual dose to each raster-point. For this purpose beam intensity, position and width are monitored in front of the patient with ionisation chambers and multi-wire proportional chambers.

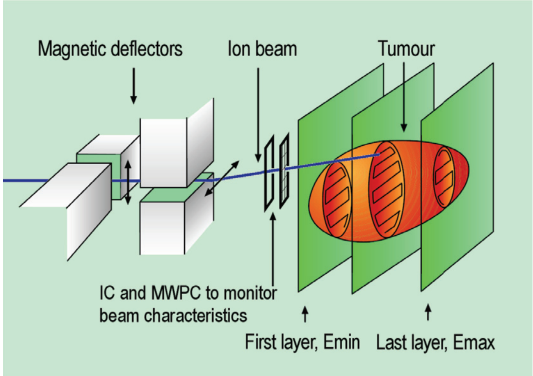

Figure 1: The rasterscan technique used at HIT [1]. The energy of the ion beam defines the penetration depth, two scanner magnets execute the lateral scanning. Diagnostic chambers are used to measure intensity, position and width of the beam.

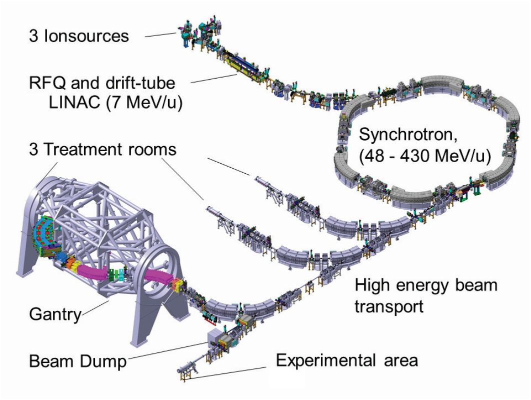

Figure 2: The HIT accelerator complex has 3 ion sources and 5 beam targets (3 of them certified for treatment). A synchrotron is the main acceleration stage that provides 255 energy steps for each ion type.

HIT Accelerator Complex

To support the rasterscanning technique a synchrotron based accelerator complex (Fig. 2) produces ion beams with a wide range of possible beam parameters. For each ion species four different beam sizes and a continuous spectrum of intensities in the range of $2 \cdot 10^6$ part./s to $8 \cdot 10^7$ part./s (carbon ions) and $8 \cdot 10^7$ part./s to $3.2 \cdot 10^9$ part./s (protons) are available. As the beam can be accelerated to more than 250 different energy steps per ion type, the penetration depth can be adjusted on a mm-scale without using any absorber material in the beam path.

Description of a Synchrotron Cycle

The main acceleration stage of the HIT accelerator complex is a synchrotron. As it is a cyclic-operating machine, phases with and without beam extraction occur, see Fig. 3. After beam injection and acceleration the particles are ex-

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tracted slowly using transverse knock-out extraction [2]. The patient is receiving dose in this phase which typically lasts up to 5 s to guarantee a correct and monitored dose application. After the extraction phase all devices are prepared for the next cycle, which usually provides a different beam energy.

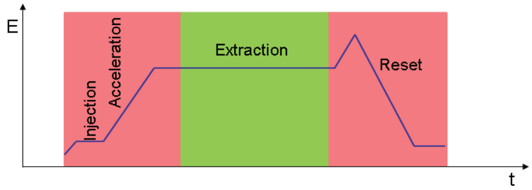

Figure 3: Typical synchrotron cycle, schematically. Y-axis: magnetic field strength of the synchrotron dipoles or beam energy. X-axis: time. The extraction level depends on the desired penetration depth and varies from cycle to cycle. Only in the green phase dose is delivered to the patient.

MOTIVATION

General Remarks to Treatment Time

Treatment time is a crucial issue in tumour therapy, several works have thus been recently brought into operation at HIT [3, 4]. For the following reasons it is worthwhile to keep the individual treatment time as short as possible:

- Higher comfort for the immobilised patient
- Higher dose conformity as the tumour is less moving
- More patients can be treated in the same time
- Higher facility performance can be achieved

The multiple energy operation scheme presented in this paper is a further possibility to reduce treatment time.

Idea of a Multiple Energy Operation Pattern

Up to now each synchrotron cycle can provide only one specific energy, see Fig. 4. To change the particle's energy, a new cycle has to be initiated. All time consuming phases before and after the extraction phase have to be accepted.

Up to now the number of accelerated particles is limited to the required number of the respective tumour slice by design. Additionally, supernumerous particles are dumped at the end of the extraction phase. However, the number of particles that can be accelerated in one synchrotron cycle usually exceeds the number of required particles by far. For therapy purposes, adjacent energy levels typically have an energy difference of only a few MeV/u.

A new synchrotron pattern is proposed that allows to reaccelerate or decelerate remaining particles after the first extraction phase, see Fig. 5. In this scenario, which is also investigated at HIMAC [5], it is not necessary to go back to the initial state at the end of every extraction period. The time for ramping down the magnets just before accelerating new particles to the adjacent energy level can be avoided.

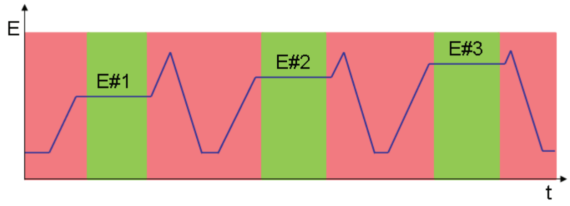

Figure 4: Three consecutive synchrotron cycles. For each energy a new cycle has to be initiated. All synchrotron devices are ramped down and up again to a slightly different energy level. The phases with dose delivery to the patient are shown in green, those needed for preparation and acceleration phases in red.

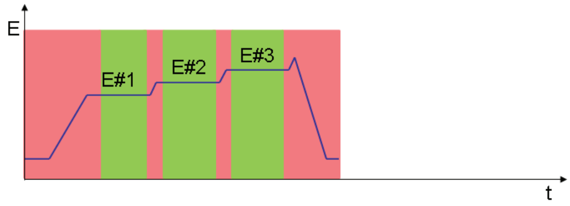

Figure 5: Proposed new synchrotron cycle, with more than one extraction energy. The ratio of the green phases with beam extraction to the red phases without dose delivery increased with respect to Fig. 4. The total treatment time can thus be dramatically reduced.

CURRENT INVESTIGATIONS

Estimating the Potential Benefit

We investigated the time benefit of such an operation scheme by analysing a representative set of 300 treatment plans applied at HIT in 2013. Based on the experience of the first 5 years of HIT accelerator operation we made the following assumptions for the simulation:

1. Changing the energy from one level to the next takes $T_{E-Change}$ = 100 ms - 500 ms.
2. The synchrotron can be filled up to a maximum number of $8 \cdot 10^9$ part. - $1.6 \cdot 10^{10}$ part. for protons and up to $2 \cdot 10^8$ part. - $4 \cdot 10^8$ part. for Carbon ions.
3. Beam losses during the acceleration from one energy level to the next are smaller than 50 %.
4. When the synchrotron is empty and a new cycle has to be started, the time between two extraction phases is T_{Refill} = 4.5 s.

These parameters are visualised in Fig. 6. By applying the simulation code (written in *Python*) to the treatment plans, we obtained the new irradiation time and compared this scenario to the irradiation time effectively achieved in 2013. The simulation showed that the treatment time can be reduced considerably. Depending on the boundary conditions for beam losses and time for reacceleration, a reduction of irradiation time by 43 % - 68 % can be achieved.

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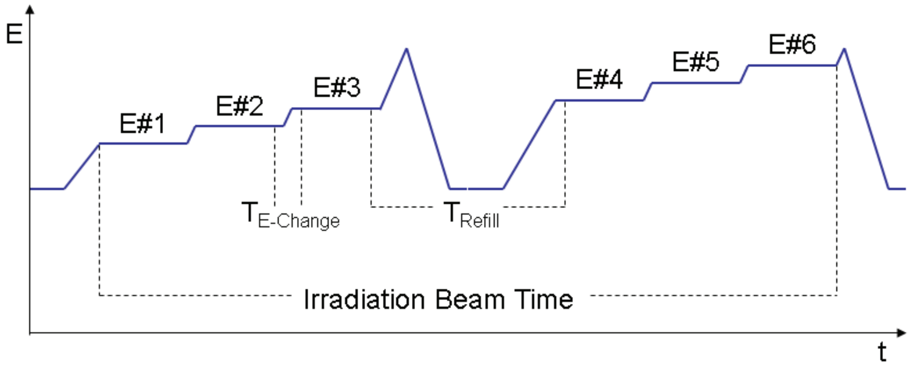

Figure 6: Two synchrotron cycles with more than one extraction energy. For the simulations the irradtiation beam time was compared. $T_{E-Change}$ and T_{Refill} indicate the time needed to change the energy without and with ramping down the magnets and inject new particles, respectively.

New Accelerator Data Supply Model

A new data supply model for the HIT accelerator that allows tests with a reaccelerated or decelerated beam is currently in progress. Almost all devices of the HIT synchrotron and the high energy beam transport section have to be provided with new set values. This includes all magnets (dipoles, quadrupoles, sextupols, steerer, scanner) as well as RF-systems (synchrotron cavity, RF-knockout exciter).

The new data supply model describes the transition from one extraction energy to another, including an additional phase prior to the acceleration. In this phase we create the possibility to vary the tune, sextupole strength or RF-parameters to find optimal settings for a reacceleration and to minimise and estimate the unavoidable beam losses.

OUTLOOK

The multi-energy operation of the HIT-synchrotron is currently in the planning and investigation stage. The following activities are planned for the coming months:

One reacceleration per cycle Only moderate changes of the HIT control system are necessary to perform tests with one reacceleration or deceleration at the HIT accelerator. With the new data supply model beam losses and the time required to change the beam energy have to be quantified.

Simulations of beam dynamics Using a simulation tool for beam dynamics the particle's behaviour in phase space can be investigated to understand the interplay of repeated transverse blow-up due to RF-knockout extraction and acceleration.

Further estimation of beam time reduction Knowing the relevant parameters in detail, the simulations can be carried out again for a larger set of patients and the time benefit can be determined more precisely.

Concept for implementation The final goal is to realise treatment plan specific energy changes in the standard operation of the medical facility. A concept for a new control system allowing for several energy levels of variable height and duration within one synchrotron cycle has to be elaborated.

Final implementation and quality assurance Before coming into operation tests by both, accelerator and medical physicists have to be completed. This includes the risk analysis and related measurements like range verification of the beam.

CONCLUSION

The investigations into a new synchrotron operation pattern to allow alternating extraction and acceleration phases have recently been initiated at the Heidelberg Ion-Beam Therapy Centre. Patients as well as the facility would benefit from a drastically reduced treatment time by up to 68 % compared to the irradiation time needed today!

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