PATIENT-SPECIFIC INTENSITY-MODULATION OF A SLOWLY EXTRACTED BEAM AT THE HIT-SYNCHROTRON

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Abstract

Since 2009 about 1500 tumour patients have been treated at the Heidelberg Ion Therapy-Centre (HIT). The HIT synchrotron produces a library of energy, focus and intensity-variable pencil beams used to deliver dose distributions of utmost conformity to irregularly shaped target volumes. The required number of particles for each volume element of the tumour, which can vary by more then two magnitudes, is applied with the rasterscan technology.

The irradiation-time and thus the patient throughput are highly sensitive to the achieved spill-structure driven by RF-Knockout extraction. Presently unfavourable fluctuations of the extracted intensity due to inhomogeneous phase space distribution of the beam are present.

Recently a feedback-loop coupling the dose-defining ionisation chamber in front of the patient with the RF-Exciter was implemented allowing for the adaptation of the extracted intensity in real-time to the patient-specific treatment plan.

The technical implementation and the impact on the clinical operation will be discussed.

INTRODUCTION

Tumour therapy with carbon ions and protons has been carried out at the Heidelberg Ion Therapy-Centre (HIT) since 2009. Up to now, about 1500 patients have been treated, approximately 50 patients are treated every day.

Rasterscan Technology

The rasterscan technology [1], see Fig. 1, is used to achieve very high dose conformity of the target volume. In this method the beam is actively controlled in longitudinal and lateral direction. The variable beam energy defines the penetration depth (iso-energy slice) which supersedes passive elements for energy variation. Two scanner magnets deflect the pencil beam to the actual rasterpoint. When the required dose is applied to the respective rasterpoint, the scanner magnets switch to the next position. For this purpose the beam intensity, position and width are monitored in front of the patient with ionisation chambers (IC) and multi-wire proportional chambers (MWPC).

To achieve the required accuracy, the irradiation time of each rasterpoint may not fall below a minimum. This means, the intensity needs to be limited. If the slice is irradiated with constant intensity, the rasterpoint with the lowest dose requirement defines the intensity for the whole

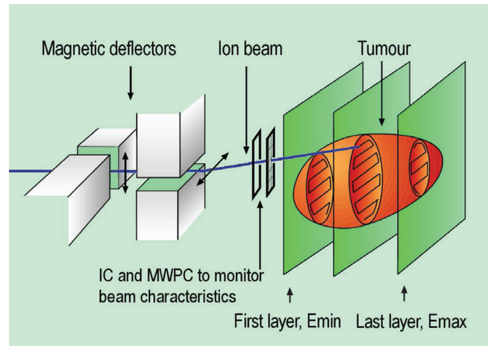

Figure 1: The rasterscan technique used at HIT. The energy of the ion beam defines the penetration depth, two scanner magnets make the lateral scanning. Diagnostic chambers are used to measure intensity, position and width of the beam.

iso-energy slice. Due to geometrical reasons and the inhomogeneous tissue, the required dose for each rasterpoint varies up to a factor of 100 even within one iso-energy slice [2]. The irradiation times for each rasterpoint vary by the same factor, see Fig. 2 left. The irradiation with an individual intensity is worthwhile, see Fig. 2 right. In this mode, each rasterpoint is irradiated with the highest possible particle rate in consideration of the minimally allowed irradiation time.

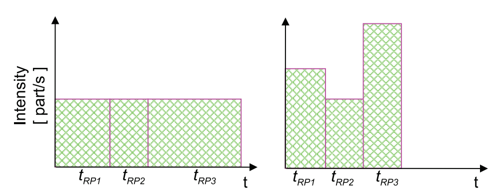

Figure 2: Left: Rasterpoints (RP) with different dose requirements have different irradiation times (t_{RP}) when irradiated with constant intensity. Right: Schematic view of a treatment plan specific intensity pattern. The irradiation time of each rasterpoint could be reduced to its minimum that has to be kept for accuracy reasons.

HIT accelerator complex

To support the rasterscan technique a synchrotron based accelerator complex (Fig. 3) produces an ion beam with a wide range of possible beam parameters: For each ion type 255 energy steps, 10 intensity levels and 4 beam sizes are presently available.

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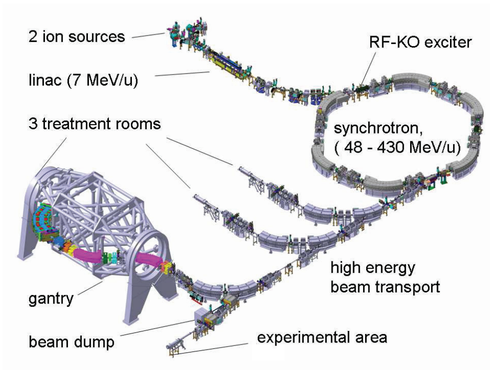

Figure 3: The HIT accelerator complex has 2 ion sources and 5 beam targets (3 of them certified for treatment). A synchrotron is the main acceleration stage.

The particles are extracted slowly out of the synchrotron using the RF-Knockout (RF-KO) method [3]. In this extraction method, the beam is partially moved into the resonance by transverse excitation.

The therapy control system sends a beam request to the accelerator control system, which contains the desired particle rate. The accelerator control system and thus also the RF-KO exciter, initiate a new cycle according to the requested parameters. The intensity at the treatment place is monitored for an accurate dose distribution.

Spill Quality

Current fluctuations appear already at the ion source. Moreover, the particles are not homogeneously distributed in phase space. Thus the predefined amplitude function of the RF-KO exciter does not lead to a smooth and flat spill, see Fig. 4. However, the time structure of the achieved intensity at the treatment place, the spill, is of utmost importance for the facility performance [2].

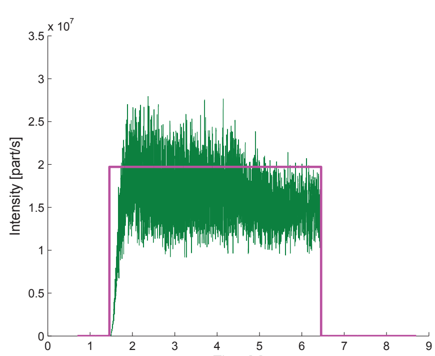

Figure 4: Magenta: Desired spill shape. Green: Typical spill achieved by RF-KO extraction at HIT. Here: Carbon beam, energy $E = 250.08\,\mathrm{MeV/u}$.

A better spill quality and an intensity modulated spill are worthwhile for the following reasons:

- Less fluctuations allow a higher intensity without risking to irradiate too fast (leads to beam aborts).
- Higher intensity means faster irradiation.
- Shorter individual treatment time means more patient comfort and lead to a higher patient throughput.
- Automatic beam aborts caused by an intensity out of range are reduced.

A feedback loop to keep the intensity on the desired level is presented in this contribution.

MATERIALS AND METHODS

To enhance the spill quality at the treatment place a feedback loop was implemented. Figure 5 shows the involved components schematically and simplified. The ionisation chambers in front of the patient which measure the intensity, are now connected with the transverse RF-KO exciter, that is responsible for the extracted particle rate.

Features of the Intensity Controller Unit

A new component, the **D**ynamic **I**ntensity switch and **C**ontroller unit (DIC), was added. The DIC selects the correct signal from the active treatment place. For this purpose, the DIC is connected to the accelerator control system. The DIC generates a correction signal according to the deviation of the reference and actual value as well as the stored feedback parameters. The correction signal is sent to the RF-KO exciter where it is added to the feed forward control.

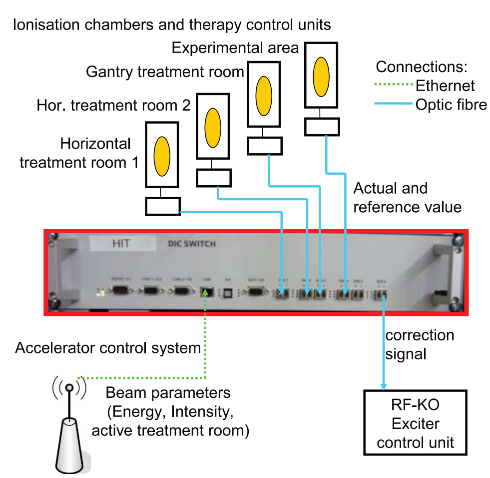

Figure 5: Schematic view of the intensity control system at HIT. Main component is the **D**ynamic **I**ntensity switch and **C**ontroller unit (DIC).

Feedback Algorithm

The controller algorithm of the DIC is a digital PID controller with the sampling time T_a:

$$G(s) = K_p \left(1 + \frac{T_a}{T_n s} + \frac{T_v s}{T_a}\right) . \tag{1}$$

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To achieve best results for the spill shape, the suitable feedback parameters K_p, T_n and T_v vary with the beam parameters energy and intensity. For each ion type, about $2\,\%$ of the possible combinations of 10 currently used intensity- and 255 energy-steps have to be adjusted carefully. An interpolation was done for the rest of the possible beam parameters and verified by tests. To find these characteristic curves, coupling beam parameters and feedback parameters, was a major effort in the commissioning of the DIC-device.

Implementation in two Stages

The implementation of the feedback loop is planned in two stages. The first stage keeps the intensity on a constant, predefined level and was implemented into clinical routine in April 2013. The second stage allows to change the intensity several times within one spill.

RESULTS AND DISCUSSION

Improved Spill with Constant Reference Value

With the closed intensity feedback loop the macroscopic spill shape can be improved as shown in Fig. 6. As the intensity is closer to the reference value as in Fig. 4, it can be raised closer to the upper limit without risking to be out of the allowed range.

The reduction of treatment time due to the feedback loop is about $15\,\%$. This means the number of patients can be increased by 4-5 patients per day to a total number of 55!

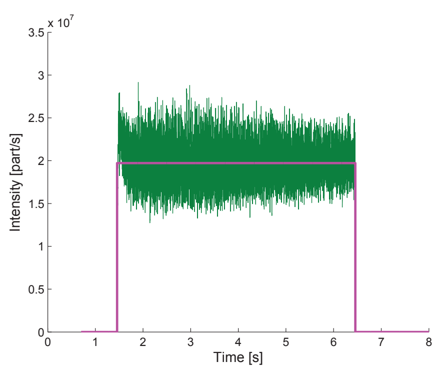

Figure 6: Magenta: Desired spill shape, reference value. Green: Typical spill achieved by RF-KO extraction AND closed intensity feedback loop at HIT. Same beam parameters as Fig. 4. The actual intensity follows the reference value.

Influence on the Therapy Quality

Each stage allows to irradiate with a higher intensity in average and thus leads to a reduced treatment time. The benefit of a faster irradiation can only be used for therapy purposes if the accuracy of the dose application is still guaranteed. To investigate the therapy quality of the ion beam, the following measurements have been carried out with and without the closed feedback loop:

- Irradiation of films to proof the homogeneity of a desired dose distribution.
- Verification of the beam position in the iso-centre.
- Verification of the calculated dose distribution with ionisation chambers in a water phantom.

The measurements showed, that the beam quality can be kept on the same high level required for therapy purposes.

Improved Spill with Intensity Modulation

The second stage of the spill control allows a treatment plan specific adaptation of the intensity. First tests were carried out successfully. They show another significant reduction of treatment time up to $30\,\%$ compared to the constant intensity. The implementation is planned until the end of 2013.

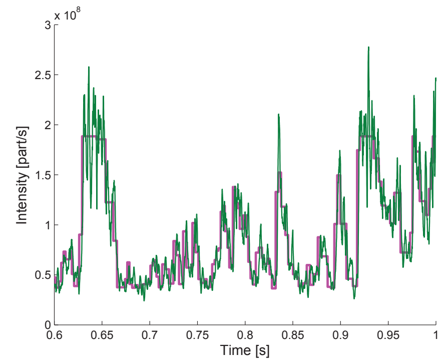

Figure 7: Magenta: Desired spill shape with variable reference value. Green: Actual value of the intensity with closed feedback loop. Here: Carbon beam, energy $E = 179.46\,\mathrm{MeV/u}$. The actual intensity follows the reference value within ms.

CONCLUSION

A feedback loop has been recently implemented at the HIT accelerator complex, that couples the dose-defining ionisation chamber in the treatment room and the RF-Knockout exciter. The system allows both, a spill with constant intensity on the predefined level as well as patient-specific intensity modulation. The energy and intensity dependent feedback parameters have been adjusted carefully. A significant reduction of treatment time is achieved.

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