IMPLEMENTATION OF AN INTENSITY FEEDBACK-LOOP FOR AN ION-THERAPY SYNCHROTRON

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Abstract

The Heidelberg Ion Therapy-Centre (HIT) started treatment of tumour patients in 2009. Its main acceleration stage is a synchrotron, where particles are extracted slowly, in the time frame of some seconds, to support the raster-scanning method. The slow extraction is driven by the transverse *RF-knockout exciter*. So far, this device has an adjustable but predefined amplitude curve. As the phase-space distribution of particles is not homogeneous and varies slightly from pulse to pulse, intensity-fluctuations of the extracted beam appear. Moreover, adjustment of the exciter for the whole energy range is time consuming. To keep the intensity on a predefined level, a feedback loop has been implemented. The actual-value of the intensity is provided by an ionisation chamber in front of the patient. The feedback loop controls the amplitude of the exciter to adapt the number of extracted particles. Beside a beam with a rectangular intensity profile, a dynamic intensity-adaptation during one spill with respect to the particular treatment plan will be investigated. First tests for both, flat spill and variable intensity, show promising results.

INTRODUCTION

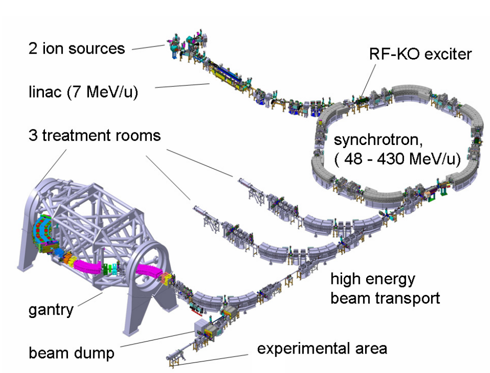

Figure 1: HIT accelerator complex.

The HIT accelerator complex can be seen in fig. 1. The particles are accelerated to their final energy in a synchrotron with an energy-range of $48-430$ MeV/u. There are 3 rooms with horizontal beam lines (2 of them certified for patient treatment), one with a rotating heavy ion gantry and one beam dump. The tumour is irradiated slice-by-slice with a step size of $\approx$ 1 mm with the raster-scanning method [1]. In this method each slice corresponds to one penetration depth and thus to one of the 250 available energies per particle species.

Present Extraction Scheme

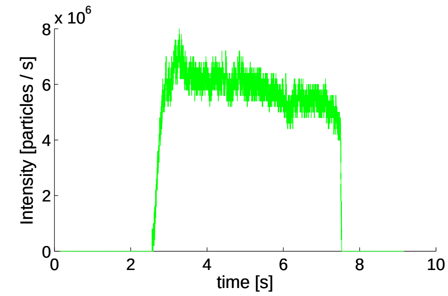

Figure 2: Typical spill achieved by RF-KO extraction. Here: $E = 423$ MeV/u. Resolution: 200 μs

A successful clinical operation requires high-quality beam properties. A rectangular spill shape over $5-10$ s with short rise time is most suitable. Additional features like spill-pause and fast beam cut-off system are realised [2]. To achieve these conditions, transverse RF-knockout extraction is used [3]. In the extraction process at HIT a third integer resonance is excited by quadrupoles, the stable phase-space area turns into a separatrix under the influence of sextupoles. The particles are then spilled out of the separatrix by the RF-KO exciter. This is the only device which does not have a constant setting during extraction flat-top and thus determines the time structure of the extracted beam. Its amplitude-curve affects the strength of excitation, its shape depends on the beam-energy. For its adjustment at least 10% of the 250 energy levels have to be considered, followed by an interpolation for the other energies.

The number of particles varies from pulse to pulse and their distribution in phase-space is not homogeneous. Hence the shape of the intensity profile cannot be exactly rectangular and constant for each spill, which would be worthwhile. A representative spill that is created by a fixed amplitude-curve is shown in fig. 2.

MOTIVATION FOR SPILL-CONTROL

Rectangular Spill

In a therapy facility, the individual treatment time should be as short as possible. This makes the treatment more comfortable for patients, as the time of immobilisation is

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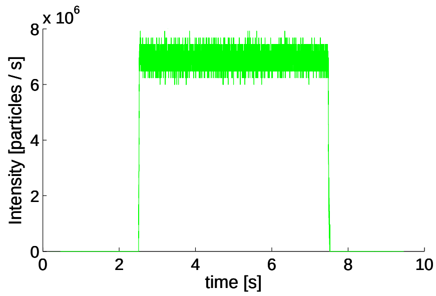

Figure 3: Rectangular-shaped spill with closed feedback-loop.

reduced. Moreover, it makes the therapy available for a large number of patients and helps to operate the facility economically. A feedback-loop for the spill intensity (also investigated in Japan [4]) which leads to a flat spill with constant intensity as it is shown in fig. 3 is worthwhile and saves time for several reasons, as presented in the following paragraphs.

The irradiation time in case of an ideal, flat spill was compared to the effective time for 420 patients treated at HIT from November 2009 until June 2011. These investigations show a theoretical reduction of the average irradiation time by up to 25 %. Right at the beginning of the spill, the rate reaches its design value very quickly (area 1 in fig. 4). This effect is very significant, as many iso-energy-slices require small amount of dose and their irradiation takes less than the maximum spill-time.

The read out of the beam monitoring chambers in front of the patients have an ADC setting that matches the expected intensity. Significant intensity fluctuations can therefore lead to ADC overflows and result in interlocks. With a spill control fluctuations and thus the number of aborts are relevantly reduced. The intensity can be tuned close to the upper boundary in order to irradiate at maximum speed (area 2 in fig. 4).

Time-consuming adjustments of RF-KO exciter settings in order to achieve acceptable spill properties will be drastically reduced.

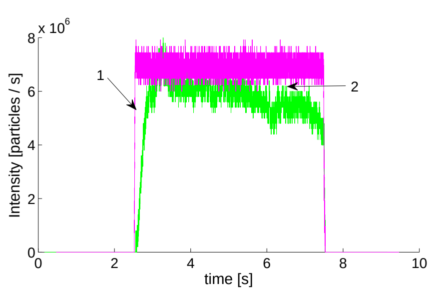

Figure 4: Comparison of spills with (magenta) and without (green) closed feedback-loop.

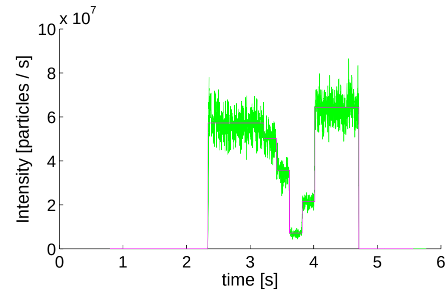

Figure 5: Spill with closed feedback-loop (green) and alternating reference-value (magenta).

Intensity-Modulated Spill

A feedback-loop offers even more possibilities than a flat spill.

If the reference value is not constant over time, other spill-shapes can easily be created, as shown in fig. 5.

This is desirable as not all raster-points of one iso-energy-slice require the same number of particles (s. fig. 6). The central-area of a slice is frequently pre-irradiated by particles stopping in distal slices and a significant dose is applied. This geometrical reason causes an intra-slice variation factor of the required number of particles of 100 or more.

Up to now, the raster point with the lowest number of particles determines the intensity for the whole slice. Points with high dose need to be irradiated accordingly longer.

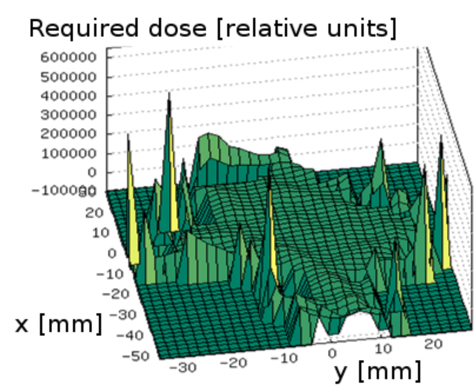

Figure 6: Typical required dose distribution of a single iso-energy slice.

With an intensity modulated spill each raster-point could be supplied by an individual particle-rate. The intensity is not fixed and predefined for a complete synchrotron cycle but adapted dynamically. The desired reference intensity is defined individually for each raster point by the patient-specific treatment plan. Experimental results show, the time to change the intensity is in the order of milliseconds, which is also the lower limit of the irradiation time of one raster-point.

Another simulation was carried out to estimate the benefit of such a dynamic intensity control. Again all treatments at HIT between Nov. 2009 and June 2011 were compared to an irradiation with each raster-point receiving the optimum intensity. Compared to a feedback-loop with constant intensity, the beam-on time can be reduced by another $50\,\%$ with carbon ions, which is the more commonly used ion type at HIT. HIT-specific boundary conditions, e.g. limitations of IC electronics, were taken into account to produce a realistic scenario.

CONTROLLER AND COMPONENTS

The set-up of the closed feedback loop is shown schematically in fig. 7.

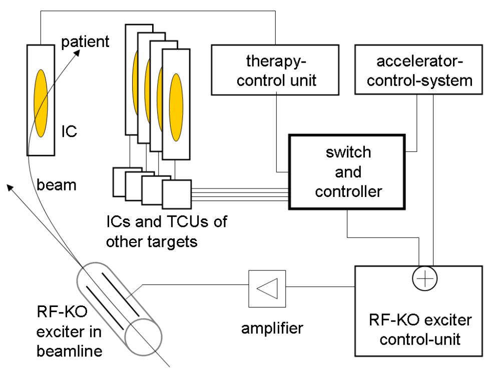

Figure 7: Set-up of feedback loop.

Besides the controller itself, actual and reference value have to be provided to realise a closed feedback loop.

The actual value is provided by ionisation chambers (IC). They are generally installed at the end of every beam line to measure the delivered beam current at any time of the irradiation to guarantee an accurate dose application. As the facility has 5 possible beam-targets (compare fig. 1) a switching unit is required to select the active target and thus the correct IC. The IC signal in units of current needs to be calibrated, which is energy and intensity dependent. Therefore the controller and switching unit has been connected to the central accelerator control system.

In a first approach, controller and switching unit are realised by a *Programmable Logic Controller (PLC)*. I/O bus-terminals are used to make actual values and status information available in the PLC as well as to output the calculated correction signal for the RF-KO-exciter. The communication between bus-terminals and industrial PC is done via real-time Ethernet connections.

EXPERIMENTAL RESULTS

Feedback Parameters

The successful creation of a flat spill with the system described above is shown in fig. 3.

The spill quality, described by the standard deviation of spill signal and reference value, defines the feedback-parameters P (proportional element) and I (integral element). A wide range of different combinations of feedback-parameters were tested and analysed. Unfortunately, they depend on energy and intensity of the beam. Tests up to now suggest that the derivative element does not need to be taken into account.

We figured out, that the P-value to achieve good spill quality changes mainly with beam-intensity, the I-value seems to be more sensitive to the beam-energy. This has to be investigated in detail.

Spill Response Time

Spill response time strongly depends on the speed of the controller, especially the integral part. One of the aims is to find feedback-parameters which generate a fast rise at spill-start, good spill quality but with no overshoot at the beginning of the spill. The controller-limit due to PLC-runtime is smaller than $100\,\mu$s. The rise time is defined as the time interval between the accelerator-signal *spill-start* and the spill reaching its reference value (Pos. 1 in fig. 4). It can be reduced to < 5 ms for 88 MeV/u and < 50 ms for 430 MeV/u if avoiding a peak at the beginning of the spill is taken into consideration. Typical numbers for rise-times without feedback loop are $100 - 300$ ms.

Changing intensity during a spill for a dynamic adaptation takes less than 1 ms for adjacent intensity levels.

OUTLOOK

The spill-control for a constant particle-rate is available at HIT and can already be used for experiments. It can be implemented into clinical routine after approval. Dynamic intensity modulation needs a dynamic reference value, too. This can be provided by any kind of function generator for tests in further experiments.

The software solution via PLC-PC will be soon replaced by a hardware-based device. This makes the system more reliable and it will then be integrated in the accelerator control-system like any other accelerator device.

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