CHALLENGES IN FAST BEAM CURRENT CONTROL INSIDE THE CYCLOTRON FOR FAST BEAM DELIVERY IN PROTON THERAPY*

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Abstract

The COMET cyclotron at PSI has been successfully used to treat patients with static tumours using the spot scanning technique, i.e. sequentially irradiating different positions inside the tumour volume. Irradiation time for each position ranges from micro- to milliseconds, with total treatment duration of about a minute. For some tumours (e.g. lung) physiological motion (e.g. respiration) interferes with the scanning motion of the beam, lowering treatment quality. For such mobile tumours, we are developing a new technique called continuous line scanning (CLS), aiming at reducing treatment time by more than 50%. In CLS, dose rate should stabilize (within few percent) within tenths of a millisecond. We thus implemented a first prototype for fast, real-time beam control: a PID controller sets the internal electrostatic vertical deflector of the accelerator, regulating the beam current output based on the instantaneous current measured just before the patient and the knowledge of the transmission from the accelerator to the patient. In pre-clinical experiments, we achieved good control of the global dose delivered; open issues will be tackled in the next version of the controller.

INTRODUCTION

Proton therapy step-and-shoot scanning techniques, like spot scanning [1] or raster scanning [2], have been remarkably successful in treating static tumours such as those located in the brain or in the spine [3]. The intrinsic dynamic of the scanned pencil beam, moving sequentially through the tumour volume in all three dimensions, is however a disadvantage when treating tumours moving periodically (due to respiration, like lung or liver): the interference between scanning beam motion and tumour motion [4–6] can deform the dose distribution up to a clinically unacceptable level (so-called ‘interplay effect’). To reduce this effect, motion mitigation techniques have been proposed. One example is rescanning [7, 8], a technique which foresees delivering the same plan several times, each time with a reduced dose, to a moving target, in this way averaging out the interference pattern between the scanning beam motion and the target motion. Though promising, motion mitigation techniques are not widely used, since they lengthen irradiation time, lowering patient comfort and throughput. Only a handful of centres worldwide offer such treatments.

Moving away from the step-and-shoot approach could potentially provide the fast, efficient irradiation suitable for motion mitigation. In this context, at PSI Gantry 2 we are developing a new irradiation technique called continuous line scanning (CLS) [9]. CLS paints an arbitrary dose distribution in the tumour volume by continuously changing the beam current and position within an energy (=depth) layer. We have shown [10, 11] that this technique can achieve dose distributions comparable to spot scanning, but reduce the treatment time by more than 50%, depending on the irradiation conditions and the motion mitigation strategy used [12].

One of the main differences between the standard pencil beam scanning delivery techniques and CLS is the way the beam moves from one position to the next during irradiation. In dose-driven techniques like spot and raster scanning the beam moves to the next position after the full dose prescribed for the current position has been delivered. This makes them robust with respect to beam instabilities, as they can compensate such effects by shortening or lengthening the time spent at a certain position; for this reason, such techniques are standard in clinical centres. Our proposed CLS implementation is instead time-driven, meaning the treatment control system (TCS) changes the values of the actuators controlling beam position and current according to a time table; this potentially makes the irradiation faster than dose-driven systems, as CLS does not rely on integrated signals to move from one position to the next. However, this poses stronger requirements on the precision of beam delivery and on the reaction time to beam instabilities, in order to avoid deformation of the resulting dose distribution.

In this document, we report about the challenges of such a system concerning beam current control, and the solution we designed for future clinical application.

FAST CURRENT CONTROL AT THE PROSCAN FACILITY

Beam Current Control in the COMET Cyclotron

The COMET [13] (ACCEL/Varian) cyclotron accelerates the proton beam used for patient treatment at Gantry 2 to an energy of 250 MeV. The beam is extracted from the proton source using a negatively charged puller, and is then accelerated passing through 4 dees. The proton source is kept at stable extraction conditions; the beam current is modulated as required by the treatments by stopping part of the protons inside the cyclotron using collimators.

Fast current changes are achieved using an internal electrostatic deflector (so-called vertical deflector, VD), which deflects the beam towards collimators built in one

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of the accelerator's dees [14]. To avoid high activation of the material, the deflector is placed close to the accelerator centre so that the protons are stopped very early, during the first acceleration turns, when they still have a very low energy. Additionally, phase slits are used to limit the maximum beam current and improve stability of operation [15].

During standard (spot scanning) patient treatments at Gantry 2, the TCS requests a certain extracted current, and the accelerator control system sets the vertical deflector accordingly; in such a mode, beam current changes can be achieved in few tens of milliseconds. For CLS, though, we aim at much faster current modulation. We have thus implemented an alternative link, which directly connects the TCS with the VD power supply, achieving beam current changes within 50 µs.

Beam Transmission

After extraction, the beam passes through a degrader, followed by an energy selection system (consisting of magnets and energy selection slits), and is then transported to Gantry 2, finally reaching the patient. The degrader causes a strong energy dependence in the transmission from the accelerator to the patient [14], compensated to a certain extent by the optics of the beam transport system.

Vertical Deflector Fast Regulation Loop

To achieve precise dose delivery in time driven mode, we need to achieve good control on the beam current reaching the patient. This means compensating for both possible transmission losses and beam current instabilities, potentially occurring during irradiation.

To this aim, we have implemented a new control algorithm for the VD power supply in the TCS. The architecture is a PID controller with a lookup table for feed forward and a dual input for feedback (Fig. 2). The goal of the controller is to regulate the beam current to the set value (fed to the controller by the TCS) within 150 µs since the start of a line.

The lookup table input to the feedforward is built from measurements of the beam current at the patient as function of the VD voltage (as those in Fig. 1). The feed forward provides a first estimation of the VD voltage set value needed for the irradiation; such value can be used to compensate for transmission variation as function of energy.

An ionization chamber, placed at the end of the gantry beam line, just before the patient ('Monitor 1' in Fig. 2), provides the input to the integral controller; such a monitor accurately measures the beam current, but due to its slow rise time (about 100 µs) cannot react quickly enough to beam current instabilities. To partially improve the latency, a secondary ionization chamber ('Monitor 2' in Fig. 2, with faster rise time than Monitor 1) feeds a proportional and derivative controller to reduce settling time after fast beam current changes.

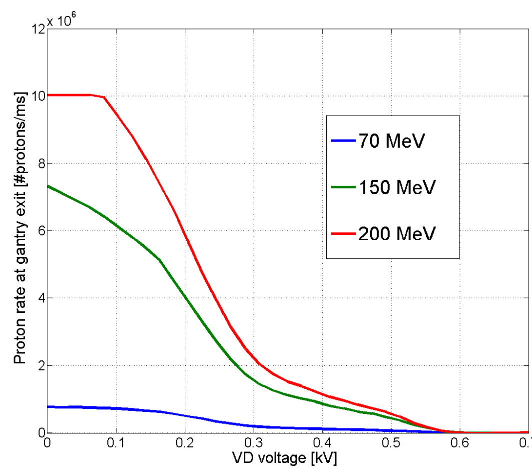

Figure 1: VD curves for different energies, measured at Monitor 1 during experiments; they show the typical shape of a lookup table used in the feedforward part of the regulation loop. The saturation effect shown at 200 MeV is due to the particular settings of the phase slits on the day of the measurement.

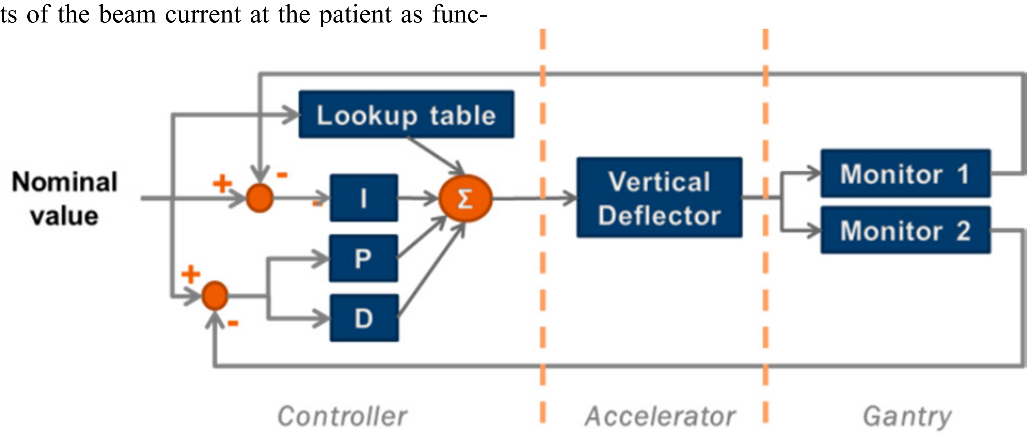

Figure 2: Schema of the feed-back regulation loop.

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RESULTS AND DISCUSSION

Lookup Table Definition and Transmission

As expected due to the energy-dependent transmission, the relationship between the measured beam current at the patient and the VD voltage exhibits strong energy dependence, as shown in Fig. 1. We also observed a rather high variability in the performance of the vertical deflector, in particular from day to day, likely due to sensitivity to changing proton source conditions.

To account for both effects, we defined an initialisation procedure that measures both the VD curve of the day for a single energy, and the transmission for a certain set point, i.e. the current output at the dose monitor as function of energy for a given VD value. The two measurements are combined by the TCS in the feedforward lookup table: the TCS scales the VD curve of the day to the energy required by the treatment plan according to the transmission function.

In experiments, we have measured an uncertainty of the order of 7% on the value estimated from the lookup table; this residual uncertainty could be easily corrected by the feedback loop, and therefore we consider this method sufficiently precise.

We are still estimating the impact of the machine conditions on the beam current output. Such effects are also compensated by the feedback loop; in case of strong variations (as could occur after a cyclotron emergency switch off, for example), the VD lookup table might not provide an appropriate initial set value and hinder the performance of the loop. We plan to implement a fast online update procedure for such cases, which will provide a new lookup table without interrupting clinical operations.

VD Power Supply Overshoot

When setting the VD in open loop, we have often observed strong beam current overshoots, lasting for more than 100 µs, thus non-negligible for fast scanning proton therapy. One example is shown in Fig. 3. The overshoot shows large variations from day to day and it is difficult to parameterise across the range of set points, but exhibits relative stability over one day. Cable capacitance and a likely impedance mismatch between the power supply and the VD are (some of) the causes behind this behaviour, and we are investigating possible hardware improvements together with the manufacturer of the power supply.

To overcome this problem, we are currently testing an improved feedforward, which accounts for the delay and the overshoot of the VD power supply in the initial set point estimation.

Regulation Loop Performance

We investigated how the performance of the regulation loop is affected by both the VD power supply overshoot and the rise time of the slowest dose monitor. The latter causes a delay in the reaction time of the loop to beam current fluctuations, which limits the usable gain of the I controller to prevent instabilities. In our new design, the integration of a faster dose monitor in the P and D controller part of the loop, together with the improved feedforward, reduces the reaction time and helps regulating for the overshoot. The result is a faster settling time in comparison to simpler designs, as shown in Fig. 4.

Because of the characteristic shape of the VD curve shown in Fig. 1, i.e. the almost inverse proportionality between the beam current and the corresponding VD voltage, the loop performs better when regulating high beam currents. At low currents, the cyclotron output is less sensitive to variations of the VD voltage. This is particularly important when using CLS with rescanning, as rescanning plans might require lower currents than standard clinical plans. We have observed that, for moderately high number of rescans (above 5), regulation issues can result in clinically visible local under- and overdosage to the target. We plan to solve this current limitation by implementing a mechanism to adapt the gain of the feedback depending on the requested beam current.

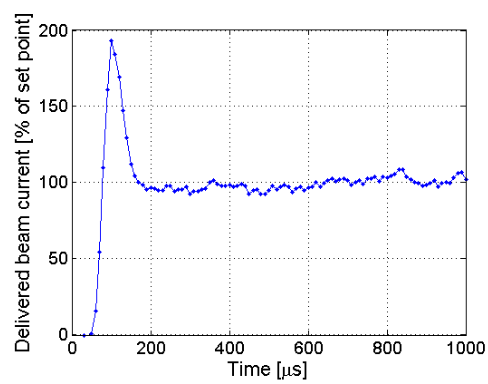

Figure 3: Example of an overshoot at the beginning of a line. Depending on different conditions, the overshoot can reach up to 200% of the set point.

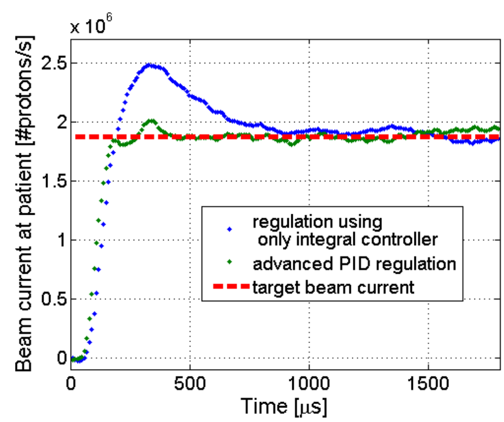

Figure 4: CLS beam current control: comparison between two options for the regulation. The advanced design presented in this work achieved the set point in about 120 µs, and does not show any overshoot, with respect to previous controller designs. A line element in a treatment can last up to several hundred milliseconds.

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CONCLUSIONS

CLS is a beam scanning technique designed to administer moving targets treatments without substantial compromises in irradiation efficiency and patient throughput. Because it is a time-driven delivery technique, it strongly relies on fast and precise beam current control. We have developed a new regulation loop for the modulation of the current extracted from the COMET cyclotron, tackling issues related to energy-dependence and stability of the beam current delivered to the patient. We achieved good precision on the delivered dose within few hundreds of µs (on a total line time of several hundred milliseconds), fitting the requirements for fast irradiation. We are currently investigating the possibility to further improve the time performance and precision by having an automatic adaptation of the regulation loop parameters, to improve beam delivery precision in low current conditions.

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