ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPML059

PRECISE BEAM DELIVERY FOR PROTON THERAPY WITH DYNAMIC ENERGY MODULATION

O. Actis†, A. Mayor, D. Meer, D.C. Weber[1],
Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland,
[1]also University Hospital of Zürich, CH-8091 Zürich, Switzerland

Abstract

Gantry 2 at PSI is a Pencil Beam Scanning (PBS) cyclotron-based proton therapy system. The main principle of PBS is a sequential dose-spot delivery to all positions (spots) within the tumour. This technique proved to be an effective treatment method for static tumours, however for mobile targets (e.g. lung or liver) organ motion interferes with beam delivery lowering the treatment quality. A common method to mitigate motion effects is to re-scan the treatment volume multiple times. One distinguishes between iso-layered re-scanning (LR) where all re-scans are performed in a single energy layer before moving to the next energy, and volumetric re-scanning (VR) where the whole tumour volume is re-scanned multiple times. Several studies demonstrate the higher effectiveness of VR [1,2]. The downside of this re-scanning type is the increase of treatment time due to high number of energy switches and magnet initializations (ramping) between scans. We developed a novel re-scanning concept which increases the dynamics of energy modulation and cuts treatment delivery times in half. Using patient file, we demonstrated that our approach with highly dynamic energy modulation allows for a beam delivery precision similar to the standard PBS irradiation.

INTRODUCTION

The PROSCAN facility [3] at PSI currently operates two gantries and one parallel fixed beamline for ocular tumour irradiation. In addition, another gantry, Gantry 3 [4], is under clinical commissioning. All treatment rooms make use of 250 MeV proton beam produced by the COMET [5] cyclotron. COMET is followed by the degrader and energy selection systems. Energies used during clinical operations and maintenance tests range between 70 MeV and 230 MeV. The Gantry 2 therapy system is a universal platform for research and development designed and constructed at PSI. The beam line and gantry elements were engineered to allow for highly dynamic energy changes of 100 ms [6]. Fast patient treatment is generally important for an efficient clinical work-flow. However, such a highly dynamic system as Gantry 2 is especially interesting for treatment of moving targets for which most likely the re-scanning techniques will have to be applied. Re-scanning is the most studied method for motion mitigation and used by many centres which are treating mobile tumours with PBS. The idea of re-scanning is simple: the target volume (tumour) expanded with the additional margins covering tumour position at all phases of motion. Afterwards the extended volume is re-scanned multiple times such that errors due to interplay between motion and beam application are averaged out. This method might be sufficient for treatment of targets with less than 5 mm motion amplitude and can be combined with other methods such as gating [7] for targets with larger amplitudes of the motion. Re-scanning alone is lengthening the total treatment time. When combined with other techniques the dead time is increased even more. For a system with slow energy changes VR will increase the treatment time by the number of re-scans leading to clinically unacceptable treatment duration. Another significant aspect introducing even larger dead time during the treatment is ramping of the beamline and gantry magnets. This procedure has to be performed to assure stable and reproducible system operation. A minor change of 0.5‰ in the magnetic field of the last gantry magnet can lead to 1 mm displacement of the beam position at the iso-center (patient). Therefore, in each re-scanning loop the system is typically forced to perform the ramping procedure.

BEAM DELIVERY WITH DYNAMIC ENERGY MODULATION

Current Default Implementation of Re-scanning

Treatment of patients with mobile tumours started at Gantry 2 in 2017. Our current re-scanning implementation is performed using a decreasing energy sequence as it is done at all other particle therapy centres worldwide. Gantry 2 system employs normal conducting magnets. Thus, to suppress hysteresis effect any standard beam delivery starts with a ramping. First, we set an energy of 70 MeV which followed by energy of 230 MeV and 5 s pause. The full procedure takes about 7 sec.

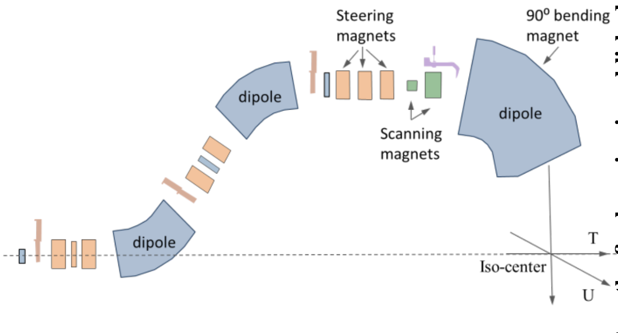

Figure 1: Schematic layout of Gantry 2 at PSI.

---

† e-mail: oxana.actis@psi.ch

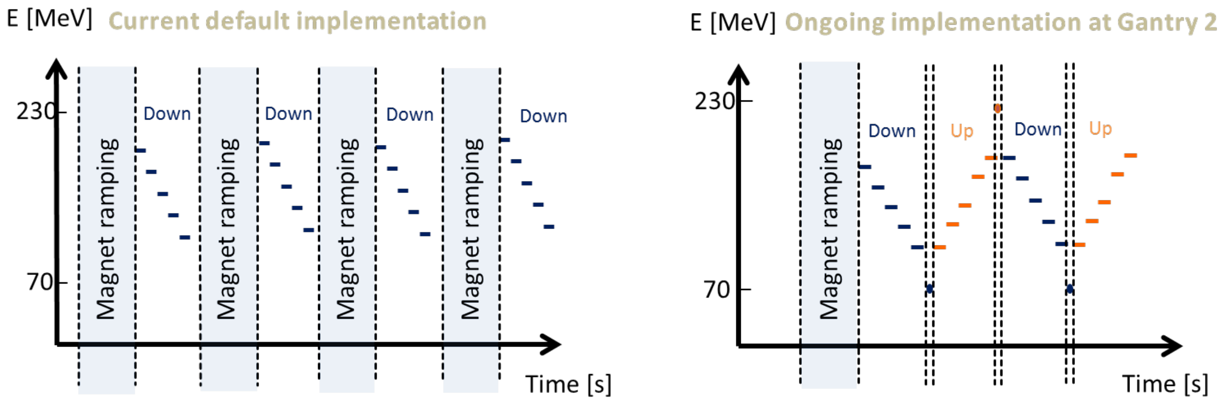

Figure 2: Current implementation of re-scanning at Gantry 2 (left). Right: ongoing implementation of re-scanning procedure with down and reverse energy directions and optimized ramping between scans.

The last 90° bending magnet on the gantry is the largest element of the system (see Fig. 1). It is placed after two scanning magnets allowing for a parallel beam at the iso-center. Thus, our system is particularly sensitive to a proper ramping of this magnet. After the first energy of the dose field is set we wait one more second and start irradiation. One scan takes from 6 s to 10 s depending on volume of the target and the prescribed dose. Each scan in the sequence preceded by ramping and repeated a prescribed number of times. Typically 4 to 8 re-scans are required to reach acceptable dose homogeneity within the target. Figure 2 (left) shows the current implementation of the re-scanning sequence. The total treatment time for this implementation with 8 re-scans is around 100s.

Ongoing Implementation of Re-scanning

In order to improve the efficiency of the mobile tumour irradiation we considered 2 possible potential improvements: commissioning of the energy changes in reverse (up-going) direction and elimination of full ramping between scans.

First, we developed beam line settings for reverse energy sequence which allow us to re-scan the target changing the energy in both directions. Choosing the beam settings, we had to make sure that the transverse beam positions as well as range of the proton beam at the iso-center remain invariant for both energy directions within allowed tolerances. Figure 3 shows the result of the tuning process. Blue markers indicate the position for down-going energies measured at the iso-center. Green markers indicate measured position for the reverse energy direction. This data was obtained using beamline settings which were delivered during the technical commissioning of Gantry 2. To correct the beam position, we used a set of steering magnets and the last bending magnet on the gantry (see Fig. 1). From the measured position offsets at iso-center we calculated the corresponding change in the currents set on these magnets. The verification run with corrected beamline settings demonstrated that the transverse beam position deviation between down and reverse energy directions is less than 0.2 mm for all energies (red markers in Fig. 3).

To validate the proton range we used in-house developed equipment. This is a Multi-Layer Ionization Chamber (MLIC) with parallel readout which is fully integrated into our control system [8]. The results for the range measurements showed a maximal deviation of 0.2 mm between beams with down and reverse energy directions. This discrepancy is well within the clinically allowed tolerance therefore we did not perform any additional corrections.

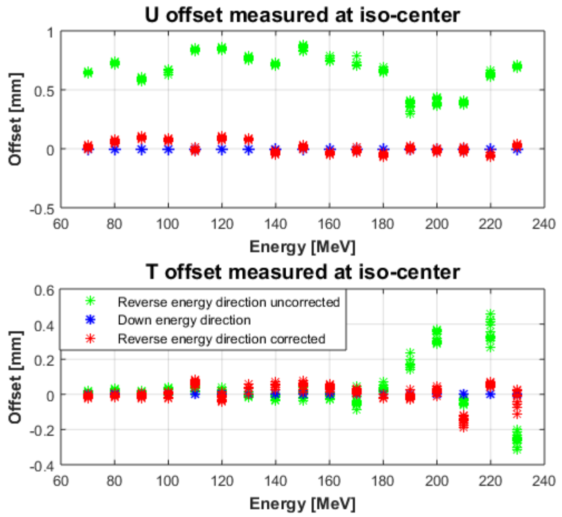

Figure 3: Results for the 'Up-direction' beam tuning in a transverse plane perpendicular to the beam line.

The second part of the optimization was the elimination of a full magnet ramping between scans. The complete elimination of the ramping would lead to a changeable offset of the magnetic field over scans since each loop will have a different hysteresis cycle. Our solution is based on the assumption that as long as we follow the same full hysteresis loop the resulting magnetic field would change correspondingly independently on dynamic of the path. This approach assures the reproducibility of the delivered beam position. The right plot in Figure 2 shows an optimized delivery of the re-scanning method containing both energy direction changes and a mini-

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPML059

mized ramping between scans. Using the optimized rescanning method a patient field with 8 re-scans will require only 50 s of irradiation time.

Patient Specific Calibration

In proton therapy the commonly used tolerance for the delivered beam position is 1.5 mm. Even though we force our magnets to repeat the same magnetization cycle there is still a possibility of inconsistency between hysteresis loops which would introduce an offset in beam position. In addition, we know that for the last bending magnet the lamination does not eliminate completely the effect of eddy currents. Thus, highly dynamic beam delivery is still leading to non-negligible beam position errors of larger than 1.5 mm. These uncertainties are field specific; therefore we compensate them by field specific corrections. Prior to the treatment each field is applied at least once during the patient verification run. The on-line position monitoring system [9] records the position of each spot during this application. Full flexibility in Gantry 2 control system allows us to feed calculated position correction offsets for each single spot back into our delivery system for patient delivery [10].

RESULTS

After the technical commissioning the final validation of the new re-scanning method for a therapy system must be performed using a real patient case. For this purpose, we used a dose plan prepared for one of the Gantry 2 patients who was treated with a re-scanning technique. We used this plan to generate machine file with 4 re-scans (same number as was used for treatment) using energy changes in both directions and optimized ramping. We used our on-line monitoring system to measure the beam position residuals for all spots of the plan. The result for this measurement is shown in Figure 4. All the dose spots were delivered with a precision of better than 1.5 mm. Dose spots containing 99.5% of the total dose are delivered with a precision of better than 0.5 mm fulfilling clinical requirements.

We used MLIC to compare the proton range of beams with the same energy which were delivered in the down- and the reverse energy sequences.

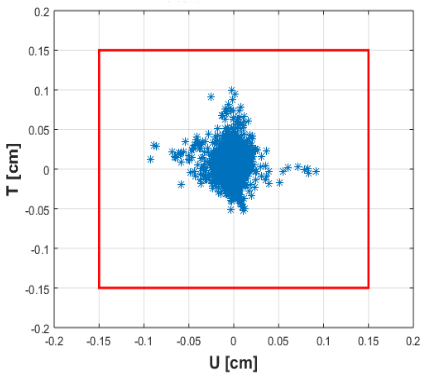

Figure 4: Beam position residuals for patient plan validation.

Figure 5 shows the results for several energies from the patient field. In general the residuals between both energy directions are better than 0.5 mm. Larger deviations were confirmed to be due to the signal quality/reconstruction problems for low-weighted dose spots.

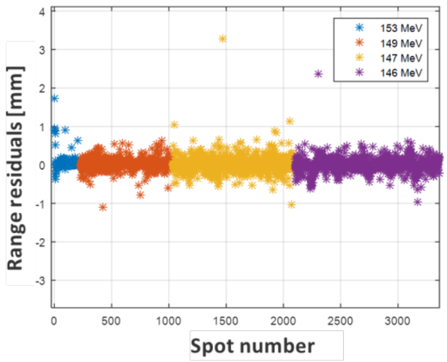

Figure 5: Proton beam range residuals between down-going and reverse energies for patient plan validation.

DISCUSSION

We demonstrated that a high beam delivery precision required for patient treatment can be maintained also for a system with highly dynamic energy modulation. The time benefit for treatments exploiting re-scanning technique can rise up to a factor of 2. For those cases where rescanning has to be combined with other motion mitigation techniques like gating the time benefit will be even more pronounced.

REFERENCES

[1] A. Schätti D. Meer, and A. J. Lomax, "First experimental results of motion mitigation by continuous line scanning of protons", *Phys. Med. Biol.*, vol. 59, no. 19, pp. 5707-5723, Oct. 2014.

[2] G. Klimpki et. al, Proceedings to the 56 Annual Meeting of the Particle Therapy Cooperative Group (PTCOG), *Int. J. Part. Therapy*: Summer 2017, Vol. 4, No. 1, pp. 14-83.

[3] E. Pedroni *et al.,* "The 200-MeV proton therapy project at the Paul Scherrer Institute: Conceptual design and practical realization", *Med. Phys.*, vol. 1, pp.37-53, 1995.

[4] A. Koschik *et al.*, "Gantry 3: further development of the PSI PROSCAN proton therapy facility", *Proc. IPAC'15*, Richmond USA, Jun. 2015, paper TUPWI016, pp. 2275-2277.

[5] H.-U. Klein *et al.*, "New superconducting cyclotron driven scanning proton therapy systems," *Nucl. Instr. Meth. Phys.*, vol. 241, pp. 721–726, Dec. 2005.

[6] E. Pedroni *et al.*, "The PSI Gantry 2: A second generation proton scanning Gantry", *Z Med Phys.*, vol. 14(1), pp.25-34, 2004.

[7] K. Ohara *et al.*, "Irradiation synchronized with the respiration gate", *Int. J. Radiat. Oncol.*, vol **17** 853–7, 1989.

[8] O. Actis *et al.*, "A comprehensive and efficient daily quality assurance for PBS proton therapy", *Phys Med Biol.*, Jan. 2017, vol.62, pp.1661–1675.

[9] O. Actis, D. Meer and S. König, "Precise on-line position measurement for particle therapy", *J. Instrum.* vol **9** C12037, Dec. 2014.

[10] E. Pedroni *et al.*, "A system for the delivery of proton therapy by pencil beam scanning of a predeterminable volume within a patient", EP2647407 A1, Oct. 9, 2013.