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Calibration assessment of the PSI proton therapy Gantry 2 scanning system after 10 years of operation

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Abstract. Sub-millimetre precision is a crucial criterion for beam delivery in Pencil Beam Scanning (PBS) proton therapy. Nowadays, most of the therapy systems use PBS technique where single beams with a regulated number of protons are delivered sequentially to different locations within the target. Beam energy defines the depth of the beam in the target and scanner magnets deflect the beam to the desired lateral position.

The PSI Gantry 2 was among the first gantries to use the PBS technique. Available clinical proton beam energies ranging from 70 MeV to 230 MeV are achieved by de-grading a 250 MeV beam, initially provided by a super-conducting cyclotron. Beam scanning is performed just before the last bending magnet producing a nearly parallel beam at iso-centre with a well-focused beam over the full scan area of 20x12 cm². We developed a calibration algorithm for the scanner magnets in order to achieve the desirable precision of the beam in the target. Measuring the beam position with a strip ion chamber in the gantry nozzle, we parametrized the propagation of the beam to the target calculating the beam angle at different scan positions as well as all gantry angles. During 10 years of operation we performed regular Quality Assurance (QA) tests to validate parameters obtained during the system commissioning. The QA data proved a stable system operation and no parametrization update was required so far. In this contribution, we describe the calibration pro-cess of scanning magnets with respect to beam position at the iso-centre and show the stability of this implementation over the time.

1. Introduction

During the last decade PBS became the most common technique for particle radiation therapy. Depending on system design lateral scanning implementation can be divided into two main categories: up-stream and down-stream scanning. In the latter case scanning is performed at the last active beam-line element just before the beam monitoring system. This design would assume first order linear correlation between sweeper current and the spot position at iso-centre. In addition, spot shape would re-main invariant for any scanning position. The drawback of such an implementation is a divergent beam resulting in dosimetric disadvantages for the patient and extreme sensitivity on longitudinal alignment at the iso-centre. For an up-stream scanning system the sweeper magnets are placed just in the front of the last dipole. Since the whole scanned field has to pass through the dipole it requires a large gap, thus larger dimensions with respect to standard dipoles. However, even if the last bending magnet has to be larger the radius of an up-stream scanning gantry is smaller than a down-stream scanning one. In addition, the up-stream scanning system allows for almost parallel beam at iso-centre (example: PSI Gantry 2 has an SSD (source to skin distance) of > 17 m), which leads to reduction of skin dose and simplify dosimetric calculations and QA tests. On the other hand, propagation through the dipole magnetic field can affect spot shape, beam focus (depending on lateral position) and beam position requiring higher order corrections for position-to-current conversion.

2. Materials and methods

Gantry 2 at PSI is an upstream scanning therapy system ensuring close-to-parallel beam delivered to the patient at all scanning locations. The proton beam is scanned over 12x20 cm² just before the last 90 degrees electromagnet which makes the calibration procedure more challenging due to non-uniform field at the corners of the magnet poles. Gantry 2 beam optics was optimized for 150 MeV, therefore already simulations performed before machine commissioning suggested a non-linear relation between sweeper magnet current and beam position at the iso-centre for energies different from 150 MeV [1,2].

2.1. Sweeper magnet calibration at Gantry 2

In order to perform the calibration of sweeper magnets, we proceeded as follows:

- Application of proton beams in a grid pattern over the full G2 scanning area using energies between 70 and 230 MeV in 10 MeV steps, repeating the procedure at all gantry angles (-30 to 180 degrees) in 30 degree steps
- Measurement and reconstruction of the delivered position at iso-centre
- Parametrization in order to reflect the current-to-position dependency: applying a smooth fit to avoid discontinuity and average reconstruction uncertain-ties

To measure the delivered beam position at iso-centre we used a strip ionization chamber (similar as we use for on-line spot position validation [3]). The chamber is located at the rotation support, attached to the patient table, which can be steered remotely. Strip chamber's automatized parallel readout is fully integrated into our control system. The detector alignment was performed using room lasers which is possible at all gantry angles. The active area of the strip chamber is slightly larger than 12x20 cm², thus in order to acquire sufficient data for a 2D polynomial fit we applied the largest possible field allowed by scanner magnets: ~14x24 cm² and selected afterward only dose spots which allowed meaningful position reconstruction.

$$I_{Usweeper}(U,T) = g_1U + g_2T + g_3U^2 + g_4T^2 + g_5U^3 + g_6U^4 + g_7U^5 + g_8U^6 + g_9U^7 + \sum_{q=1}^{4} l_1^qUT + l_2^qU^2T + l_3^qUT^2 + l_4^qU^3T + l_5^qU^2T^2 + l_6^qUT^3 + l_7^qU^4T + l_8^qU^3T^2 + l_9^qU^2T^3 + l_{10}^qUT^3 \quad (1)$$

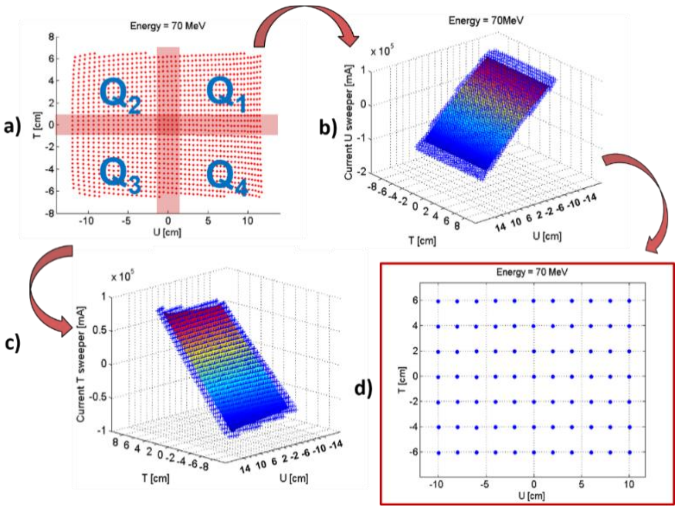

Figure 1: Graphical illustration of sweeper calibration process at Gantry 2: a) measured spot positions; b,c) blue crosses – measured data and colour gradient is a surface fit for U (b) and T (c); d) beam positions measured at iso-centre after implementation of current-to-position calibration.

A surface fit was performed on different sections of the scanning area as shown in figure 1(a) separately for both transverse directions (T and U) and all measured energies. The full expression for the data fit contains a global function (central cross-like area) and four local functions for each quadrant. The mixed terms of the local functions guarantee a continuous transition at their intersection lines. The U direction fit function is shown in equation (1) where the global and local fitting components are indicated separately. A similar function is applied for trans-verse direction T.

Figures 1 (b,c) show the data measured at iso-centre using 70 MeV beams and gantry rotated to 0 degrees (blue crosses). The colour gradient represents a smooth 2D fitting function for both transverse directions. Once the resulting calibration had been implemented, we validated all beam positions over the treatment scanning range. In figure 1(d) one can see a 70 MeV spot grid measured at the iso-centre after the calibration process had been completed.

2.2. Nozzle back-projection

Each pencil beam at Gantry 2 is validated on-line using two dose and one position monitors located in the gantry nozzle. While the beam current does not change from nozzle to iso-centre, beam position can be different due to the beam not being ideally parallel. Thus, the data from nozzle position monitor has to be translated to iso-centre by means of calculating the beam angle for all positions over the scanning area in both orthogonal scanning directions.

Daily beam position fluctuations at Gantry 2 are close to 0.2 mm at the iso-centre, thus our goal was to keep the precision of calibration measurements better than 0.2 mm. Taking into account the maximal distance between iso-centre and the nozzle strip chamber (~70 cm) we had to measure the beam angle with a precision of better than 0.5 mrad. Here we used only the nozzle strip chamber relying on precision and high reproducibility of the nozzle motion. Figure 2 illustrates the principle of beam position calculation at iso-centre. First, we measured the beam position at 2 nozzle extractions (1 cm and 27 cm) over 12x20 cm^2 scanning area with 2 cm grid for all energies between 70 and 230 MeV in 10 MeV steps. Second, we calculated the beam angles (θ, ϑ) separately for each measured energy at each grid point. This allowed us to create a lookup table (LUT) used further for on-line position verification where any beam position can be translated to iso-centre using linear interpolation.

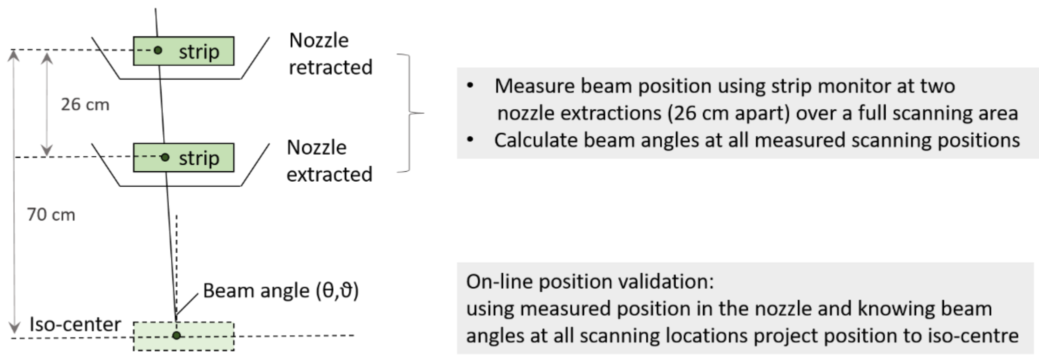

Figure 2: Schematic illustration of the workflow going from measurement of the beam angle in both orthogonal directions to on-line beam position calculation at iso-centre.

3. Results

We performed sweeper magnet calibration and created a nozzle back projection LUT for the first time in 2012 during commissioning of Gantry 2. In 2015 we repeated the procedure to refine the beam delivery precision. Our goal was to always keep beam delivery precision better than 0.5 mm at iso-centre for all gantry angles at all beam scanning locations. To guarantee these beam delivery parameters we perform regular QA tests. One of those tests checks the precision of sweeping: a spot grid is applied over the full Gantry 2 scanning range at different energies and different gantry angles. Figure 3 shows the spot position residuals in both transverse directions measured for all scanning positions and energies as a yearly QA over 10 years of system operation. Note, that outliers which are especially notable during the first years of operation are related to signal reconstruction which was improved in the course of Gantry 2 operation.

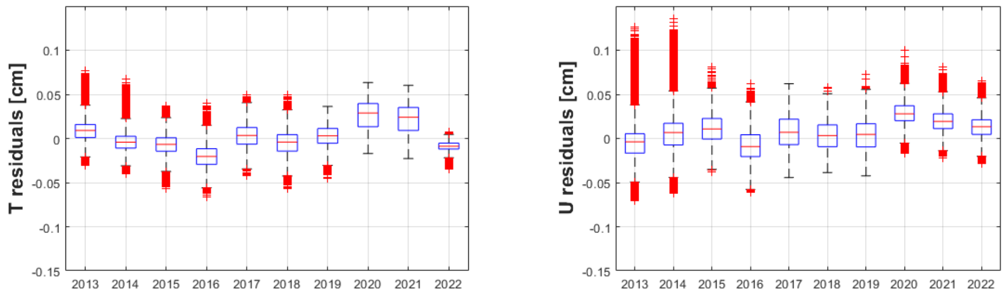

Figure 3: Overall beam position residuals measured in the nozzle and projected to iso-centre in two transverse directions at Gantry 2 (2013-2022).

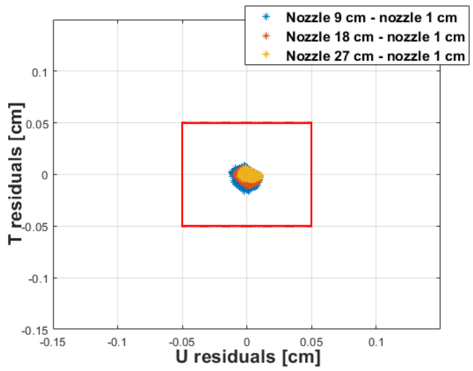

Figure 4: Lateral beam position residuals in TU between fully retracted nozzle and several nozzle positions.

Figure 4, instead, demonstrates a recent (2022) validation of beam angle parametrisation (θ, ϑ). Here, using the original LUT (produced during the Gantry 2 commissioning), we obtained beam position residuals between different nozzle extractions (9 cm, 18 cm and 27 cm) and a fully retracted nozzle. Beams with energies ranging from 70 to 230 MeV were applied at gantry rotated to 0 degrees over the full Gantry 2 scanning area. The red box indicates the clinically desirable range for position residuals of 0.5 mm. As one can see here, all deviations do not exceed ±100 µm confirming the stability of machine operation and beam optics preservation over the years.

4. Discussion

In this contribution we showed the necessity of sweeper magnet calibration and explicitly the challenges of such a procedure for up-stream scanning system. Even though the calibration process is time consuming and has to be performed carefully, we were able to demonstrate high reproducibility over the years with no need to repeat the calibration unless major system changes occur.

References

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