A NOVEL GANTRY FOR PROTON THERAPY AT THE PAUL SCHERRER INSTITUTE

E. Pedroni, T. Böhringer, A. Coray, G. Goitein, M. Grossmann, A. Lomax, S. Lin, M. Jermann
Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

Abstract

PSI has gained in the last few years the unique experience of using a proton therapy system based on a beam scanning delivery technique and on a compact gantry. This knowledge is now bringing forth new initiatives. We are continuously producing significant modifications and improvements to the present system, gantry 1. The major new step is however the decision of PSI to purchase a dedicated accelerator for the medical project. In the context of the expansion of the medical project of PSI (project PROSCAN) we have also started to plan the realisation of a second proton gantry, gantry 2. In this lecture we present the main ideas for the novel gantry, which will be based on one hand on the experience with the present technology, but on the other hand should be designed as a system more open to further developments and needs. The established and the future requirements for the beam delivery on the new gantry were routed into the specification list for the dedicated accelerator.

1 INTRODUCTION

The vision for the future aimed at in the proton therapy community, is to reach the point where we can treat with clear advantages about 10% of the medical indications treated with conventional radiotherapy. Since the availability of industrial solutions is still in its infancy and the experience is scarce, the choice between different technical solutions is still a matter of debate. A proton facility should be planned considering not only the experience of the past, but also the state of the art of radiation therapy and the foreseeable future developments of the field. Since a proton facility represents a long-ranged investment - the lifetime of the facility is at least 15 to 20 years - the best technical solutions are those which are open to possible future enhancements. In this paper we present the strategy of PSI for realising a long-term competitive proton facility. Our main guiding line is the belief that the future of proton therapy will be characterised by dynamic beam scanning methods and by the use of compact gantries. These ideas are based on the positive experience acquired utilising the present gantry system.

The next goal is the conceptual design of a second new compact gantry dedicated to beam scanning, capable of competing with the most recent methods developed in conventional therapy, *intensity modulated radiotherapy with photons* (IMRT) and capable at the same time of substituting completely the scattering foil technique. This approach should permit a larger spread of proton therapy in the hospitals.

2 BEAM DELIVERY

2.1 The choice of the beam delivery technique

A major concern, when designing today the layout of a dedicated hospital-based proton facility, is the question, which beam delivery technique to choose:

- static by *passive scattering ?*
- or dynamic by *beam scanning* ?

The idea to choose a system capable of delivering both methods on the same gantry is probably a very safe approach, but requires many compromises, adds much to the complexity of the system, and could be in the long term a too expensive solution.

2.2 The scatter foil technique

The past and most of the present of proton therapy has been governed by the *scatter foil technique.* This method was developed in physics laboratories with horizontal beam lines and is now used in all dedicated *hospital-based proton facilities* realised since the beginning of the ‘90s. The leading example is the facility of the Loma Linda University in California. In the USA a second facility is expected to go into operation in Boston this year. Several similar facilities are already in use (Kashiwa, Chiba) or are presently being built (Tsukuba, Shizuoka, Hyogo) in Japan.

All these systems are characterised by a “long throw” gantry, a rotating beam line that spans a diameter of about 10-12m. The scattering foil technique is based on the idea to scatter the proton beam in such a way as to obtain a homogeneous proton fluence in the solid angle covering the tumour. The shaping of the dose is then performed using individual collimators and compensators. The modulation of the proton range is obtained using a spinning wheel (the so-called range-shifter-wheel, which interposes a time-varying amount of material in the beam).

2.3 The spot scanning technique

In this case the proton pencil beam coming from the accelerator is delivered directly into the patient. Individual pencil beams are added under computer control to provide an individually shaped dose distribution with

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maximal conformity to the target volume (using variable modulation of the range). In the lateral direction the beam is usually scanned by magnetic deflection in the beam line ahead of the patient. The modulation in depth is achieved by changing the range of the protons dynamically. A high conformity is achieved by changing the dosage and the position of each pencil beam individually under computer control.

At present the proton facility of PSI is the only one capable of delivering proton therapy using a dynamic beam scanning technique [1]. The only similar system of beam delivery is the scanning system realised at GSI in Darmstadt (Germany) [2] for carbon ion therapy (with a fixed horizontal beam line). The system of PSI is also the only scanning system available on a gantry.

2.4 The future of conventional radiotherapy

The so-called *intensity-modulated-radiotherapy* (IMRT) with photons is judged to become in a very near future the major competitor to proton therapy. These new dynamical methods will soon represent the state of the art for precision therapy using conventional equipment. The prevalent opinion in the hospitals is that proton therapy is strongly challenged by these new methods.

Beam scanning is in this respect the ideal method for delivering a superior intensity-modulated-therapy using protons. With protons one can modulate independently both the *beam fluence* AND the *proton range* simultaneously, as a function of the gantry angle (simultaneous optimisation with computer algorithms of *all parameters*, intensity, range and beam incidence of individual proton pencil beams). To distinguish it from IMRT we should call more properly this method *range-intensity-modulated proton thera*py (RIMPT).

The feasibility of RIMPT has been recently demonstrated at the compact proton gantry of PSI [3]. That RIMPT needs to be implemented in the future proton therapy facilities is probably just a question of time.

The development of proton IMRT on a system originally conceived for the scattering foil technique is technically difficult. Our strategy is to use a dynamic beam scanning method to provide RIMPT, and to improve it in such a way that it can to some extent simulate scattering (in order to achieve a better compatibility with the more established methods of proton therapy of the past).

3 THE PSI GANTRY: GANTRY 1

The PSI gantry system is still the only system delivering proton therapy by active beam scanning. For more information we refer to the PSI medical division home page [4].

3.1 Gantry mechanics

The major achievements of the PSI gantry are:
- A very compact gantry design.

The diameter (4m) of the PSI gantry is reduced by about a factor of 3 compared to all alternative designs based on passive scattering. With the scatter foil technique the broadening of the beam is almost impossible to be started in the beam line ahead of the last bending magnet without loosing the homogeneity of the field. The drift space for the broadening of the beam must thus be added to the gantry radius. This is why gantries capable of delivering scattered beams are all necessarily large and bulky.

By combining the beam scanning technology with the beam optics of the gantry we were able to design the most compact gantry system of the world. On the PSI gantry the patient table is mounted eccentrically on the gantry and rotates with the gantry. This reduces the gantry radius further, but the fact that the patient table is moved over a circle of 2 m is the most criticised point of our design. A possible alternative solution for a compact gantry with the patient table at the isocenter is discussed in section 5.

- Large solid angle (of beam incidence on the patient).

The (axial) gantry angle can be changed continuously over 360°. For head treatment the patient can be also rotated by ±120° in the horizontal plane. Possible modifications of the present layout for gantry 2 are discussed in section 5.

3.2 Beam delivery

The PSI gantry is dedicated solely to beam scanning.

In the present system we use a single device for each one of the three scanning axes (keeping the system simple, safe and reliable). The beam is scanned inside the dispersive plane using a sweeper magnet before the last 90° bending magnet (the most often used motion, with a lateral 20 cm scan range and a 30ms time for a full sweep). The scan in depth is performed with a range shifter device (36 polyethylene plates moved sequentially into the beam - with single steps in proton range equivalent to 4.5mm in water - one plate with half thickness). The last and slowest motion is performed with the patient table.

Following goals were fulfilled in designing the PSI scanning method:

-Full flexibility to deposit a “dose spot” (the dose maximum of the pencil beam at the Bragg peak position) at any position and with any dosage (time exposure) inside the patient body using a parallel proton pencil beam of 7–8 mm FWHM. We deliver routinely 3d-conformal therapy with protons with variable modulation of the range.

- Complete parallelism of the pencil beam.

The beam optics of the last bending magnet is designed to provide a complete parallelism of the scanned beam. The same is almost impossible to achieve with scattering. The advantage of having a Cartesian movement of the beam is an easier approach for treatment planning due to the absence of beam divergence (infinite source to skin distance). The orthogonality of the scanning axis is also useful for expanding the field size beyond the range of the magnetic scanning by shifting the patient table.

-Reduced neutron dose background compared to scattering.

-Automatic dose delivery under computer control.

-No need for patient-specific or field-specific hardware. This contributes significantly to the efficiency of the system. For the application of sequential dose fields the automatic change of gantry angle is possible without any intervention of the personnel inside the treatment room.

- The most important advantage compared to scattering is however the capability to deliver non-homogeneous dose distributions and by this to get access to new IMRT techniques with protons.

3.3 Experience acquired with the present system

The PSI system is operational since 1996. The medical indications comprise presently only skull, base of the skull and tumours in the low pelvis. 72 patients were treated on the PSI gantry by the end of the year 2000.

The PSI system is the only existing prototype of a system dedicated to beam scanning on a very compact gantry. From the practical experience of using the facility for patient treatments, we have learned a lot on the strengths and on the weaknesses of our system. Part of the experience is now flowing back in a number of undergoing changes and improvements for gantry 1.

The major point is the re-optimisation of the whole patient handling and of the details of the geometrical shape of the patient table and of the nozzle. Since we provide the modulation of the proton range with a range shifter system in close vicinity to the patient, it is very important to always be able to place the patient very close to the nozzle. The broadening of the beam due to the multiple Coulomb scattering in the range-shifter plates increases linearly with the *air gap* between range-shifter and patient. A large air gap can thus spoil considerably the achieved quality of the dose distribution. This is the main point of the ongoing redesign of the environment and of the functionality of the nozzle and of the patient table for gantry 1, which should be ready beginning of 2002.

3.4 The organ motion problem

Organ motion is a problem common to all new dynamic beam delivery techniques, *including IMRT with photons*. Radiotherapy will ask in the future for IMRT methods applied also to the abdomen and to the trunk. For this we need advanced beam scanning techniques (section 5.3).

The organ motion problem is presently our major weakness towards the goal of providing a complete substitution of the scattering method with a compact scanning gantry.

The scattering method is by construction less sensitive to *organ motion* than scanning and this is probably the only but very important merit compared to scanning.

With scattering the dose is deposited gradually over the whole target volume. The large number of volume repaintings (due to the high speed of the range shifter wheel) averages out the dose homogeneity errors produced by the motion of organs inside the patient body. Organ motion effects are then present only as a blurring of the edges of the dose distribution.

Presently with our scanning method we paint the dose only once (or just a few time) over the whole target volume. Organ motion can therefore disturb significantly the homogeneity of the dose inside the target volume.

This is the main reason why *at PSI we treat presently only well immobilised tumors, located in the head and in the lower pelvis.* In order to replace completely the scatter foil technique with scanning and make it obsolete, it would be necessary to upgrade the beam scanning technique, such that it can be used safely also for the treatment of moving targets. If we could show that beam scanning is capable of covering all the old established situations and at the same time can provide RIMPT, the major obstacle against the use of compact gantries as a general solution for new hospital-based proton therapy facilities would disappear.

3.4.1 Coarser beam scanning

As a first approach we envisage the delivery of the beam scanning on a very coarse grid of points using *larger beam sizes* in the interior of the target. By reducing the number of grid points we should be able to implement several multiple repaintings of the target volume. By avoiding sharp gradients of the pencil beam and by increasing the statistics of repaintings, we could diminish the dose homogeneity errors due to organ motion in the interior of the target. If the large beam spot is used also at the target border, we may add *collimators on top of such a coarse scanning (simulation of scattering).* Unfortunately the nozzle of gantry 1 was not designed for use with defocused beams (for this we are in the process of replacing the range shifter with a new one with a larger transverse aperture).

3.4.2 Respiration phase triggering

Another interesting more precise solution would be *to trigger the dose delivery or even to steer the beam as a function of the phase of the breathing cycle*. This would not only reduce the homogeneity errors inside the target volume but would also improve the precision of the dose fall-off at the edge of the target. This idea is also part of the development program for gantry 1.

3.4.3 Faster beam scanning

A long-range attractive approach would be to improve the speed of scanning. A much *faster beam scanning* method would provide the possibility for multiple target repaintings without increasing the beam size and without the need for collimators. For this approach we need modifications which are not possible on gantry 1. For this we need a new gantry design (section 5).

4 THE PROJECT PROSCAN

The success achieved with the compact gantry for proton therapy has motivated the directorate of the Paul Scherrer Institute to extend our R&D activities. An important step is the planned installation at PSI of a *dedicated accelerator* for our medical project and the further development of the spot scanning technology. A major goal aimed for this expansion, the so-called PROSCAN project, is the technology transfer of proton therapy with the spot scanning technique to major hospitals. In this context we are also starting the design of a second proton gantry, which should be added to our facility after the commissioning of the accelerator. The second gantry is intended to be a commercial version of the present gantry system and will be optimised for a hospital environment. The new system relies on the practical experience of using the first prototype for patient treatments but will contain several important improvements.

5 CONCEPTS FOR A NEW GANTRY 2

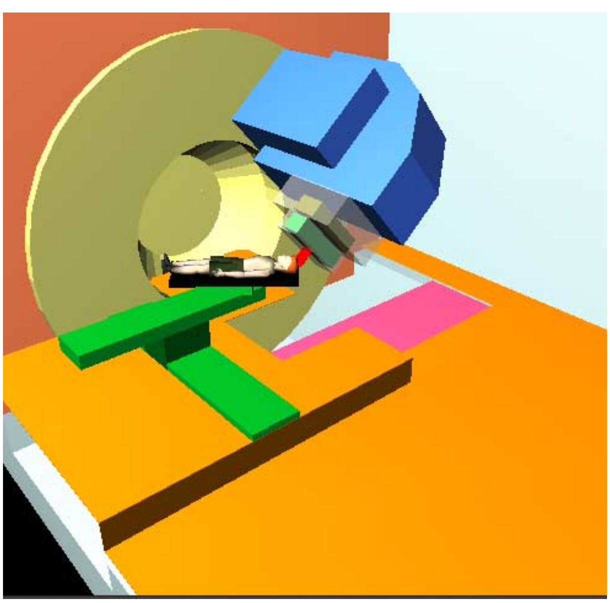

Figure 1. Possible layout for the new gantry (tentative).

5.1 A new gantry layout

The major goal here is to provide an easy access to the patient table at any time on the basis of a fixed permanent floor (without losing any flexibility in the choice of the angle of incidence of the beam on the supine patient). We propose to build the next gantry with the patient table at the isocenter (fig.1). The gantry radius will be somewhat larger than with gantry 1 (3 meter instead of 2 m), but still significantly smaller than any other existing design. We propose to limit the gantry rotation to +,-90° from the vertical on one side (eventually 270°) and to install the patient table in the gantry pit on the opposite side. This leaves enough space for a large fixed floor on 3 sides around the patient table. The table shall be able to perform an almost complete rotation in the horizontal plane (the details of the patient table are not fixed yet: possible options include rotation with rails, long axial table or a robotic system).

5.2 Moving nozzle enclosure

For the next gantry we propose to move mechanically the nozzle shield during scanning, by exactly the same amount as undergone by the patient on the patient table. In this way the nozzle will not show any apparent motion with respect to the patient. This will not only reduce the risks of collisions during beam scanning but will also provide a supporting frame for mounting individually (large) shaped apertures and compensators in front of the patient (as possible optional devices). Due to the motion of the patient table during scanning this is not possible on the present gantry (the exception is the use of small collimators which can be fixed on the patient table).
The aim here is to provide more compatibility with the established passive scattering method.

5.3 Improved scanning methods

We plan also to include in the design several options for future developments and improvements of the scanning method.

5.3.1 Energy variation with degrader

As a first option we shall investigate the possibility for a fast dynamic energy variation in the beam line ahead of the gantry. A very fast degrader shall take over the role of the range shifter in front of the patient. This option would make the spot scanning method less dependent on the patient distance from the nozzle.

The major difficulty is the fact that the beam line must cope dynamically with the changes of energy during scanning. Another problem is expected from the fast loss of beam intensity at the lowest energies (when using a cyclotron with degrader). The increased sharpness of the distal fall-off of the Bragg peak at low energy could also be quite problematic, since it could imply a very large number of energy steps for the stacking of Bragg peaks required to obtain a flat Spread-Out-Bragg-Peak (SOBP). For these reasons we prefer to keep both options open, a range shifter in front of the patient and a fast degrader at the exit of the cyclotron.

As a first orientation, we attempt to achieve with the degrader and the beam line the same speed as with the range shifter of gantry 1 (typically 50ms for a 5mm change in proton range). Our conviction is that a rather fast dynamic variation of the energy is needed for providing a true *volumetric* target repainting. A very effective fast rescanning method should not only imply the magnetic rescanning of the plane transverse to the beam but should also include repeated scans in depth.

5.3.2 Double magnetic scanning

For a new gantry we would provide the option to use a second fast lateral magnetic scanning, with the second scan direction transverse to the gap of the last 90°-bending magnet. With two magnetic axes we should be able to perform a much faster volumetric repainting of the target volume than with gantry 1. Instead of applying long spots statically to the full dose, we would deposit portions of neighbour spots more "simultaneously" (using smooth filter functions applied on the required intensity pattern). In this way we would attempt to deliver the dose more sparsely without the appearance of long-lasting local sharp gradients.

The new axis of scanning will be confined within the gap of the last bending magnet (a scan range of 6-7cm may be a possible choice). We want to keep the 90° bending magnet close to the same size as it is now, without compromising too much the dimensions and the power consumption of the compact gantry. For the (new) transverse direction we expect to achieve a much higher speed of scanning than for the (old) dispersive direction. On one side we will gain speed by keeping the range of the scan limited within the gap. Because of the weaker focusing of the 90° bending magnet in the transverse direction we will need also less bending power for achieving the same beam displacement. The dose for large target volumes will be delivered as the sum of several partial fields. Each partial volume will be deposited with multiple repaintings and with smooth edges at the interior of the target. The addition of the partial fields shall be performed by moving the patient table only a few times.

Just from first order transport calculations it seems possible to preserve the beam parallelism also in the second transverse direction (i.e to conserve the complete orthogonality of scanning). The second very fast magnetic scanning is expected to be most effective in combination with the intensity modulation described below. All these ideas and their feasibility need more detailed studies.

5.3.3 Intensity modulation with the ion source.

For the project PROSCAN we plan to use a cyclotron. We shall study the practical utilisation of beam intensity modulation from the accelerator using a vertical deflector plate in the central region of the cyclotron. The same device shall be used as a replacement or as a backup for the kicker-magnet. The intensity modulation will be eventually used in combination with the second continuous magnetic scan motion described before.

An ambitious goal would be to scan with the second sweeper magnet at constant maximum possible speed (> 1cm/ms) and to shape the dose only by modulation of the intensity at the beam source (with 0 to 100% intensity changes in about 100 μs).

6 CONCLUSIONS

All these ideas clearly underline our preference for the use of a cyclotron followed by a degrader. This choice has an essential advantage compared to a synchrotron, the delivery of a very stable D.C. beam. The good duty factor is a very important requirement for scanning.

From the point of view of the cyclotron specifications [5], the reliability and stability of the delivery of the beam is of paramount importance.

The domain where new developments are wanted from the accelerator specialists, is the work of providing a precise dynamic control of the beam intensity to the end (medical) user. The vertical deflector plate in the central region of the cyclotron is probably the most important point of development. For this a new collaborative effort between accelerator division and medical divisions of PSI (and industry) will be undertaken in the frame of the new project PROSCAN. We need the intensity modulation option if we want to improve the speed of scanning, in order to cope with the organ motion problem and to provide new modern IMRT beam delivery techniques.

PSI is the ideal place where to keep a new commercial gantry as a reference for performing these new necessary technical developments. The new scanning methods, once developed and tested at PSI, shall be implemented later on the clone systems of the hospitals, as it is done for software releases.

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