The use of protons in cancer therapy at PSI and related instrumentation

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Abstract. Novel irradiation techniques in cancer treatment, such as e.g. proton or ion therapy are developed to minimize the volume of healthy tissue that is irradiated. Since a few years facilities are being setup in hospitals for routine use, but at the same time many technological developments are still needed for further optimization of the treatment strategies in a hospital environment. These developments concentrate on accelerator design, dynamic beam delivery techniques, beam delivery systems that allow beam direction flexibility (gantry), dosimetry and system reliability. An overview of these developments is presented, with an emphasis on those for the PROSCAN project at PSI.

1. Introduction

At the Paul Scherrer Institut (PSI) in Villigen, Switzerland, a long tradition exists in the exploration and research of radiation therapy with heavy charged particles. With the use of pion beams in the eighties, experience has been obtained [1-3] in the use of beam scanning techniques and the treatment of very large tumors. In the nineties this technique has been adopted to perform radiation therapy with a scanned proton beam on a gantry. In the meanwhile a successful program of eye treatments with 72 MeV protons had been started. However, more and more the proton therapy program has been hampered by the constraints of the beam facility at PSI. The major disadvantages are namely, that the gantry uses the proton beam from the large 590 MeV proton cyclotron parasitically in a multi-user environment and that this cyclotron has shut down periods of about four months per year for service and upgrades. Therefore in 2000 the decision was taken to expand the proton therapy activities at the PSI into a dedicated facility and the so-called PROSCAN project was launched. The project’s objectives are: 1) further development of the PSI Spot-Scanning technology into a new gantry, which can be implemented in a hospital environment (i.e. with faster scan methods to deal with the organ motion problem), 2) optimization of the treatment methods, including treatment of mobile tumors, and 3) transfer of the technology and of the know-how to industry and to radiation therapy centers, including education and training of specialized personnel.

The new facility (figure 1) consists of a dedicated 250 MeV cyclotron, energy degrader, beam lines, therapy equipment (the currently existing gantry, a new gantry and a new eye treatment facility) and a beam line for experiments. It has been designed to be capable of providing reliable stable beams of varying energy during the whole year. Currently (2005) the facility is under construction and the
cyclotron and beam lines are commissioned. The first patient treatment is expected in the second half of 2006.

2. Beam delivery techniques and results at PSI

Several methods are currently being used to spread the dose of a proton beam effectively over a tumor volume [4]. The classical way to deliver a proton beam is with the so called scattering technique. In this technique the relatively small beam from the accelerator is broadened by foils in the beam. Just before the patient the beam shape is defined with a collimator. The collimator aperture matches the shape of the beam to the tumor shape, as seen from the direction of the incident beam. The largest penetration depth of the protons is set with a Lucite disk, mounted between the collimator and the patient. Since the needed maximum penetration depth in the patient is not the same over the whole beam cross section, this disk (bolus) is machined to the needed thickness, which varies over the disk cross section according to the needed penetration depth. The Bragg peak is smeared out in depth by means of a rotating Lucite wheel of varying thickness, located near the scattering foils.

Although this beam spreading technique is used at most proton therapy centers, it has several disadvantages. First of all the dose distribution is not optimal: the dose in the healthy tissue located in front of thinner parts of the tumor, receives the same dose as the tumor. Also one can not vary the dose over the beam cross section. A second major disadvantage is that the bolus and collimator are patient and field specific. The modulator wheel is also field dependent, but can be chosen from a library of wheels. One has to enter the room to install these three components for every field. For relatively simple treatments or small and single fields, these disadvantages are not so severe and for treatments of the eye this technique has proven to be very successful (figure 2). Since 1984 more than 4200 patients (mostly with eye melanoma) have been treated with this technique at PSI [5,6], with an overall local control of more than 98% at 5 years.

For the larger and deep seated tumors the so called pencil-bam scanning technique has been developed at PSI [7]. Then one scans the Bragg peak of a proton beam of 7-8 mm diameter in 3 dimensions over the tumor, by applying the dose on a discrete 3D grid of 5 x 5 x 5 mm³ voxels (or “spots”). In the current gantry at PSI (figure 3) the two transversal movements of the pencil beam are done with a fast scanning magnet and a patient-table motion respectively and the third dimension (in depth) is done by varying the beam energy just before the patient by inserting Lucite plates (range shifter) in the beam. With the pencil beam scanning technique one can make a very inhomogeneous dose distribution per field (figure 4), optimized to achieve a desired dose distribution in the tumor and a low dose in the surrounding tissues [8-10].
Disadvantages of this scanning method are the beam spreading caused by multiple scattering in the Lucite plates (yielding less sharply demarcated dose distributions) and the time loss due to the relatively slow motion of the table. Further, as with any dynamic treatment technique in radiation therapy, a disadvantage of the scanning beam is the dose inhomogeneity caused by movements of the tumor or organs during the scanning process. Due to such movements, severe under- or over dosage may occur. This has confined the selection of tumor sites that has been treated at PSI to those sites where organ motion is very limited. Since the start of the use of this technique at PSI in 1996, there has been a steady increase of treatments of patients with a chordoma or chondrosarcoma at the skull base or along the spinal cord. The treatment results [11,12] of these tumors show a three year survival rate of 89-93% (depending on the tumor site), which can be regarded as extremely good. Since the pencil beam motion is parallel, the maximum field size only limited by the table-shift range. This allows the treatment of very large tumors, e.g. elongated along the spinal cord (figure 5).

In order to be able to treat also tumors at sites where organ motion must be dealt with, a new gantry design has been made for the PROSCAN facility, which will be discussed below.

Figure 2. The OPTIS facility at PSI for eye irradiations with protons. The patient is fixed in a dedicated chair and moved in front of the beam aperture.

Figure 3. The existing gantry at PSI for pencil beam scanning in 3 dimensions, by magnetic deflection, shifting of the range with lucite plates and table motion, respectively.

Figure 4. Dose distributions obtained with scanning proton beams. Per field (left) highly inhomogeneous dose distributions are used. An optimization of 4 field yields a homogeneous dose distribution in the target and an excellent sparing of the critical tissues.
3. Facility layout

The new PROSCAN facility is being built within an existing PSI experimental hall (see figure 1). Where possible, use is made of moveable concrete elements, so that crane access is possible at all sites. An important boundary condition during the various construction phases was the continuation of the program of the existing gantry, which is located in the same hall. The patient treatment program with the existing gantry will continue until the end of 2005, using the beam from the 590 MeV cyclotron.

The beam extracted from the new cyclotron, will be adjusted onto the axis of the beam line with two xy-steering magnets. A quadrupole triplet focuses the beam onto a degrader, which has been designed for fast beam-energy changes. In order to limit the emittance of the degraded (and scattered) beam, and to define the acceptance of the beam transport system, the degrader is followed by two collimator systems. Behind the collimators, an analyzing system selects the beam momentum, with a maximum spread of ±1.2%. The analyzing magnet and the momentum selection slit are part of an achromatic beam transport system, so that the beam transport to the treatment room is almost insensitive to small deviations from the nominal magnet settings. A point-to-point imaging with intermediate images transports the beam to so called checkpoints at the entrances of the user areas. The beam optics has been designed such that the lens settings are independent of the specified possible beam emittances. All magnet settings scale similarly with beam energy, which can be done sufficiently fast by using laminated magnets. The beam size is set by the collimator apertures only.

During a test phase, the reliability and performance of the cyclotron will be evaluated using a beam line up to the entrance of the new gantry area. A research program to test new beam-scanning concepts, dedicated dosimetry equipment for beam scanning, and control aspects will also be carried out in this phase. During the spring of 2006, the existing gantry will be connected to COMET. In 2007 the installation of the new gantry and the new eye treatment room will commence.

4. Components of the PROSCAN facility

4.1. Accelerator: cyclotron

4.1.1. Cyclotron versus synchrotron.

For the proton accelerator one has the choice between a synchrotron and a cyclotron. Nowadays both types of accelerators are offered by commercial companies as “turnkey” products. The advantage of a synchrotron is its capability to accelerate a variety of particles (when not explicitly designed for protons) to an adjustable energy. Therefore a degrader is not needed. However, due to the spill structure of
a synchrotron, the beam cannot be used efficiently and the advantages of the pencil-beam scanning technique cannot be exploited to their full extent. When the particles of a certain energy are no longer needed (e.g. while the specified dose of particles with that energy has been reached), one has to wait until the next beam spill. Also, when a spill is completely used, one needs time to wait until the next spill. Intensity modulation and fast scanning are also not yet possible, due to the large unpredictable variations of the beam intensity.

Until now no cyclotrons exist that are able to combine the capability of accelerating protons and carbon ions to a sufficiently high energy. Also the beam energy of a cyclotron is fixed. This means that the beam has to be degraded to the desired maximum energy in a treatment. Unfortunately this goes together with the activation of material due to beam losses and scattering in the degrader. However, using a proper choice of materials and an optimized design the created radioactivity is mostly short lived, and only created at very well defined locations. Important advantages of a cyclotron are that its beam intensity is very stable, adjustable accurately within only a few tens of microseconds, has a DC character and is available when desired. Since a cyclotron does not need an injector accelerator (e.g. a proton linac) and the needed vault is much smaller than for a synchrotron, the costs of a cyclotron are considerably lower. Above considerations and the choice not to go for carbon ions, have made PSI decide to choose for a cyclotron as proton accelerator in the PROSCAN project.

The chosen cyclotron (named COMET, figure 6) is based on a design of H. Blosser, NSCL, (USA) and has been manufactured by ACCEL Instruments GmbH (D), in close collaboration with PSI [13]. The cyclotron accelerates protons to 250 MeV. The magnetic field is made by means of a set of superconducting coils. An important specification is the high extraction efficiency, to minimize the amount of radioactivity in the machine. This aspect is important for the other important specification, a high availability, similar to normal radiotherapy equipment. An intensive collaboration between ACCEL and PSI, led to a design that aims to fulfill these requirements.

Figure 6. Schematic overview of the 250 MeV super conducting cyclotron, developed by ACCEL, in collaboration with NSCL and PSI
4.1.2. Reliability as a design concept

Design aspects related to a high availability of the cyclotron are e.g. extensive monitoring tools in the HF system. All cooling circuits in the cavity are separately monitored with a flow switch and a temperature sensor. Furthermore, the exchange of service-sensitive components has been made relatively easy, and in the commissioning phase the last iteration steps will be done after exercising with PSI service staff.

We experienced that, in addition to the advantages of the high magnetic field from the superconducting coil, a stabilization of the room temperature and a relatively low temperature rise in the cavity cooling-circuits, will lead to a very reproducible magnetic field, which is a primary requirement for the reproducibility of the beam line tune.

The (micro-)spark detection circuits [14] in the low level part of the HF-amplifier, are provided by PSI and operate analogous to those for the 590 MeV cyclotron. Due to the possibility of distinguishing so called micro-sparks from larger discharges, the HF need not switch off completely at every spark. It is expected that this will also enhance the availability of the beam. A rigorous set of acceptance tests will start in the fall of this year. In addition to the beam and technical parameters, also aspects regarding service and availability will be subjected to tests.

First beam of this new type of cyclotron has been extracted in April 2005. During the commissioning phase the extraction efficiency has increased steadily and has reached its design goal of 80% in October 2005.

4.2. Degrader

In the new gantry, a fast beam-scanning technique in three dimensions will be applied: two lateral scans by fast steering magnets and one scan in depth by adapting the beam energy. This will be accomplished by a degrader and laminated magnets in the beam transport system. A range change of ~5 mm in water (this corresponds to ~1% change in beam-momentum) has to be set within 50 ms. The degrader [15] consists of a pair of multiple wedges, (figure 7) covering a energy setting in the range of 70-238 MeV. We have chosen multiple wedges to increase the multiple scattering at the high energies, so that a smaller dynamic range of the beam intensity from the ion source is required. Furthermore it is more compact than a single wedge system. It has been mounted in a vacuum box, which also contains beam intensity monitors, beam profile monitors, a beam stopper (all before the degrader) and a beam size defining collimator, immediately behind the degrader. To allow short service times, but also because these and neighboring components will become radioactive, special handling tools and transport systems have been constructed. The need to limit the radioactivity due to activation has led to a careful choice of materials and a minimization of the amount of material.

![Figure 7. The degrader unit, consisting of beam diagnostics, a mechanical beam stopper, the degrader pair of multi-wedges and a collimator system.](image-url)
4.3. Beam interruption concept
The beam will be switched on and off by the user (see section 5). In a first phase of the project, the main switch will be a fast kicker magnet that can deflect the beam within 50 µs. In a later phase, use will be made of a deflector mounted in the cyclotron center. When activated, this will stop the beam in the first few orbits, which prevents the production of radio-active material. For longer interruptions, also the HF will be set to a reduced power. Since no beam is accelerated then, activation is prevented. Furthermore, for safety reasons, the ion source must be switched off before staff can enter the vault.

4.4. Beam diagnostics
Several beam diagnostic systems will control the beam parameters in the different modes of operation [16]. Ionization chambers and secondary emission monitors will be used as current monitors and, in a multi-strip configuration, as profile monitors for the beam lines. Thin monitors, which will always be in the beam, will be used for continuous measurements (intensity and transmission verification) and “thick” monitors will be inserted in the beam for tuning purposes only. To prevent a patient treatment with a monitor still left in the beam, the thickness of these monitors has been chosen such that the beam transmission suffers enough to trigger an interlock signal from the transmission verification system.

For fast measurements of the beam energy and momentum spread, a multi-layer Faraday cup has been developed and tested. A copper version will be mounted on an actuator in the beam line and an aluminum version will serve as a “table-top” device for the commissioning of the cyclotron and degrader.

New VME-based multi channel electronics for the diagnostics have been developed [17]. Remote verification whether the detector is intact is possible via the connected electronics. In order to allow quick access and minimal deterioration due to radiation damage, all electronics are placed outside the vaults.

4.5. Pencil beam dosimetry and monitoring
Dosimetry and monitoring of quickly varying beam characteristics require new developments, processing of high data rates, and high absolute accuracies. Together with the Technical University of Delft (NL) a new type of dosimetry equipment, based on a scintillating gas, is being developed for scanning proton beams [18]. The system (see figure 8 for a schematic overview) consists of a parallel...
plate ionization chamber, from which the electrons are multiplied and accelerated in a gas by a so-called Gaseous Electron Multiplier (GEM) [19]. During the gas multiplication process, also gas molecules are excited and decay by fast light emission [20]. Since the amount of emitted light is proportional to the dose deposited in the ionization chamber, the shape of the light spot shows the two-dimensional dose distribution, similar as obtained with a scintillating screen [21]. It has been shown that the advantage of this detector over a scintillating screen is that it does not suffer from signal quenching in the Bragg peak.

4.6. A new compact gantry
The new gantry (figure 9) will be equipped with two fast sweeper magnets, by which the beam is scanned in the two lateral directions [22]. These magnets are located before the last (90 deg.) bending magnet of the gantry, which has a large gap, to increase the space in the direction orthogonal to the bending plane. The beam optics is designed such that the magnetic scanning evokes a fast parallel motion of the pencil beam in a 20 x 12 cm plane at the isocenter. Since in the scanning process all motions are orthogonal to each other, larger fields are conveniently reached by a shift of the patient table. The needed penetration depth (i.e. energy) of the pencil beam will be set with the degrader discussed before. This design will allow a very fast complete coverage of the tumour, so that multiple rescanning can be done.

Another change of the design with respect to the existing gantry, is the use of an isocentric patient table, which has been combined with a gantry rotation at one side of the patient only. This has lead to a better access of the patient at all gantry angles. Even with a patient table at the isocenter of the gantry rotation, the radius of the gantry has been confined to 3.5 m, which is still considerable smaller than the 6 m of the “classical” gantries for proton therapy.

Figure 9. Overview of the new isocentric gantry at PSI
5. Patient safety: dedicated responsibilities

An important design aspect in PROSCAN is a rigorous separation of the responsibilities of cyclotron and beam lines from those related to the treatment equipment. This decouples the tasks and responsibilities of the “machine” as beam delivery system and a “user” who decides whether the beam is accepted or not for a treatment. Before each treatment room, a so called checkpoint has been defined, where the beam should comply with specifications on energy, position, direction, emittance and intensity. For each beam energy, the “machine” will use a predefined setting of the beam line (a “tune”) and by means of collimators and dedicated beam diagnostics at the checkpoint (plus dedicated read back from energy defining elements), the user has to verify if the beam characteristics satisfy the user’s needs. This illustrated in figure 10. This separation is also present in the control system architecture. A “Machine Control System” (MCS) controls the accelerator and beam lines and it only checks the machine performance itself. Each user area has its own “User Control System” (UCS), which decides to take the beam or not. Each UCS communicates with the MCS via an allocation system. When the beam is allocated to a certain user area, its UCS will obtain the so called “mastership” over the facility. The Master-UCS will then ask the MCS to set a tune and independently of the MCS it will start, verify, use and stop the beam.

6. Conclusions and outlook

The results obtained with proton therapy at PSI have shown that protons offer unique possibilities to treat tumors at locations where sparing of healthy tissue is of utmost importance. The dosimetric characteristics of protons are known up to the level of a few percent. Doses can be and are applied with a very high accuracy, both geometrically and, since the radiobiological effect of protons is well known, also with respect to the magnitude of the biological dose.

The successful experience with the spot scanning technique developed at PSI has led to the start of an extension of the proton therapy program and a prototype facility for hospital based proton therapy.
is under construction presently. The design especially aims at a high availability of the system and a full exploitation of the scanning beam technique, enabling the treatment of moving organs and targets, with a new compact gantry.

Tests with beam have been started in 2005 and in the meanwhile the new dedicated 250 MeV cyclotron has reached most of its specifications. This made us having confidence to stop the current proton therapy program at the existing gantry and start to connect this gantry to the new cyclotron. The first patient treatment on the existing gantry is planned in 2006. The new gantry will be installed in 2007.

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