CANCER THERAPY WITH 200 MEV PROTONS AT PSI. DEVELOPMENT OF A FAST BEAM SCANNING METHOD AND FUTURE PLANS FOR A HOSPITAL BASED FACILITY.

Eros Pedroni†, Reinhard Bacher†, Hans Blattmann†, Terence Boehringer†, Adolf Coray†, Mark Phillips*†, Stefan Scheib†

† Division of Radiation Medicine, Paul Scherrer Institute
CH-5232 Villigen-PSI, Switzerland

* Research Medicine and Radiation Biology, Lawrence Berkeley Laboratory,
1 Cyclotron Road, Berkeley, CA 94720, USA

Abstract

A new project for the treatment of deep seated cancers using proton beams has been started at PSI. The results of the first tests of the development of a fast beam scanning application technique (magnetic deflection of the focussed proton beam) performed in 1989 at PSI are summarized in this paper. The plans for the future construction of a beam line dedicated to proton therapy together with the new design of a very compact gantry are presented in the second part of the report. A very brief discussion on ideas and problems about a future hospital based facility for Switzerland terminates the presentation.

1.Introduction

The physical properties of proton beams are expected to bring significant improvements in cancer therapy by their large potential of improving dose localisation[1,2,3].

At PSI experience with cancer therapy with charged particles beams spans many years. Since 1981, 482 patients have been treated with negative pions using a dynamic scanning method developed for a 60 converging pion beams geometry (Piotron)[4].

Since 1985, 840 patients have received radiation treatment for uveal melanoma cancer (OPTIS project) using a 70 MeV proton beam at PSI [5].

The third new project of the medical division of PSI, namely charged particle therapy for deep seated tumors using protons of 200-250 MeV. is now underway [6,7,8].

Protons with variable energy and intensity suitable for proton treatment were available for test experiments starting from July 1989 at PSI. The beam is obtained by degrading the protons from 590 MeV (proton current of about $20\mu A$) down to energies near 200 MeV (proton current of about $1nA$). The beam is reanalysed in momentum and phase space in the second part of the beam line after the degrader. The present setup is provisional and is not adequate for the treatment of patients. The beam has been used in 1989 for the development of a new method of application of radiation, a **fast scanning of the focussed proton beam** inside the patient. Technical specifications and first results obtained with our apparatus are presented in section 2 of this report. Since the results were encouraging, the design of a new beam line dedicated to proton therapy has been proposed at PSI, accompanied by the design of a very compact isocentric gantry (with dimensions similar to those used for conventional treatments). These topics are briefly discussed in section 3. The final goal of the project is, however, to contribute to the realisation of a hospital-based proton facility, adapted to the needs of a small country like Switzerland.

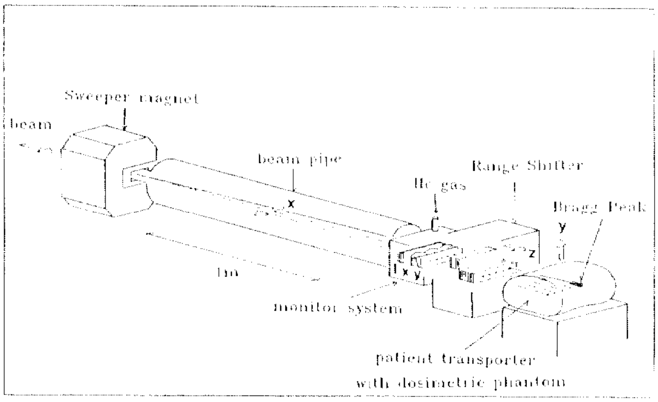

Figure 1: Layout of the experimental setup for the tests of the spot scan method.

2.Development of the spot scanning technique

The new dynamic treatment developped at PSI is based on the superposition of discrete dose spot applications. The dose at each single spot is well localised in space (in the lateral direction by maintaining the beam focus and in depth by the presence of the Bragg peak characteristic of all charged particle beams). The dose at a given position is applied by switching on the beam, measuring the quantity of applied radiation while the dose is being accumulated and by switching off the beam when the desired dose value for the spot has been reached. The focussed proton beam is then moved to the next spot position and the cycle is repeated. The full scan is performed under computer control by scanning the beam in three dimensions inside the patient's specific target volume, defined by the therapist using modern diagnostics like CT and MRI.

The basic apparatus is shown in Fig.1. The switching on and off of the beam is performed by a *fast kicker magnet*. The measurement of the dose delivery is performed with a *dose monitor* system. The motion, which is most often executed (in our case the horizontal) is performed by the magnetic deflection of the beam with a *sweeper magnet*. The depth of the beam in the patient is controlled by a *range shifter* system. The motion which is least frequently used is the vertical one and is performed by moving the phantom with a *patient transporter* system.

The advantages of the spot scanning method compared to the conventional method with passive scatterers in the beam is summarised in the following paragraph.

The dose can be exactly tailored in three dimensions according to the anatomical extent of the tumor (**three dimensional dose conformation**). The dose distribution may be shaped, if desired, according to a non-homogeneous dose prescription. The treatment is fully automated, multiple field irradiations are therefore performed more efficiently. Individual hardware like collimators, compensators, range shifter wheels, etc. can be avoided for routine treatments (but can be included as an option for special indications). A very small compact gantry can be designed for the spot scanning technique.
The "discretisation" of the spot applications makes the method insensitive to beam instabilities. The electronics performing the dynamic treatment and the devices necessary to guarantee the safety of the treatment are simpler to realize for the discrete than for a continuous scan method.
The discrete spot scan technique easily permits the synchronisation of the treatment with the phase of breathing of the patient. The problem of organ movements during treatment and related dose errors, are discussed in a separate report [9].

Specifications for the dynamic scanning.
The spot size at the Bragg peak has dimensions of about 0.5 to 1.5 cm FWHM in the three directions,depending on the energy of the beam. We assume that scanning with the beam should be performed on a grid with a mesh size of typically 5 mm. Assuming a treatment volume of 1 liter and an irradiation time of about 2 minutes we calculate a total of about 10000 spots and a mean irradiation time of 12 ms per spot. If we want to control the dose at each spot individually at the 1% level we need to be able to switch off the beam with a reaction time of 120 μs.The apparatus depicted in Fig.1 has been designed to satisfy these general specification goals.
The components in Fig.1 have been constructed and tested in the NA1 beam line during the beam period of 1989.

Fast kicker magnet.
Function: On-Off switching of the beam. The kicker magnet is a laminated C-shaped magnet with an effective field length of 23 cm and a magnetic field of 0.5 kGauss. The power supply allows the switching of the current in the magnet from 0 to 50 Amperes in 100 μs with a rather high repetition rate (spot times as short as a few ms). The kicker magnet has been installed about 2.5 meters upstream of the last bending magnet of the beam line. A copper collimator with a horizontal slit of 4 mm width has been placed inside the gap of this bending magnet. The beam optics of the beam have been chosen with a sharp vertical focus at this collimator location. When the kicker is powered, the beam is deflected in the vertical direction by about 1.2 cm and is then completely stopped in the copper plate of the collimator.We measured the reaction time for the switching off of the beam by recording the rate in a small scintillation counter during the beam-on time and immediately after. The reaction time has been measured to be 50 μs.

Integral dose monitor.
The monitoring of the dose is done with plane parallel ionisation chambers (gap 1 cm) covering the full beam (thin aluminized mylar windows mounted on rigid modular frames). The chamber modules are placed in a box filled with helium gas (at about 1 atmosphere) and are operated with 1 kV voltage, to guarantee a fast collection of the charges (ions and electrons) produced by the radiation in the gas. With 1 kV the overall reaction time of the full dose delivery system (fast kicker magnet controlled by the ionisation monitor) has been measured in the beam to be 135 μs.

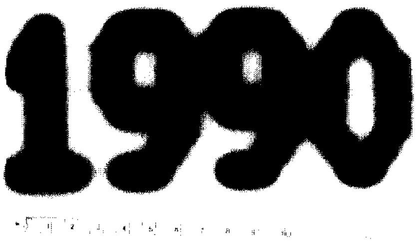

Figure 2: X ray film irradiated with the 200 MeV proton beam using the spot scanning method.

Position-sensitive monitor system.
The most frequent motion of the beam is performed by the sweeper magnet (see below). In order to check (on line) the proper functioning of the sweeper system the position of the deflected beam is measured immediately in front of the patient for each spot deposition during treatment. A position-sensitive helium monitor chamber has been built and placed in the same helium box as the integral monitor. The high voltage plane of this chamber is tilted with respect to the two parallel ground planes collecting the ionisation charges. By taking the ratio I1/(I1+I2) of the charges collected on both sides of the tilted foil it is possible to measure the centroid of the beam. In the case of the x motion, the tilted foil has been shaped like a zigzag profile. Reproducibility measurements of the charge ratio recorded for time intervals as short as 5 ms were performed showing a position resolution better than 0.5 mm.

Range shifter.
The range shifter system consists of a stack of 40 polyethylene plates, each 4.5mm thick and with a size 2.5 cm x 20 cm in the direction perpendicular to the beam covering the entire region of the swept beam. The plates can be moved individually into the beam by pneumatic valves (but can be removed only collectively with the full stack). The time delay needed to bring one plate in the beam has been measured by an optical system to be less than 30 ms. The time for removing the full stack is longer (around 100 ms).

Sweeper magnet.
The magnet for sweeping the beam is of the same design as the fast kicker, but with a different power supply. The beam can be swept over a region of $\pm 10cm$ in the patient at a distance of 2.5 m from the magnet by changing the magnet current over $\pm 400Amp$. The sweeping speed has been measured to be faster than 1cm/ms.

Simulation of dynamic treatments.
With the full apparatus as described above we performed first tests for the spot scanning method.
Fig.2 shows the capability of the spot scanning method to shape the dose according to very irregular target volumes. The X-ray film has been irradiated with the proton beam at 15 cm depth in the water phantom. The hardware used for the test for dynamic treatment with protons has been found to be within the original specifications. Although the treatment planning system for irregular volumes and with inhomogeneities has yet to be developed, the technical feasibility of the spot scanning technique has been demonstrated in practice.

3. Proposition for a dedicated proton facility at PSI

The next step of the project is the realisation of a new beam line with a dedicated area for the treatment of patients with a horizontal beam. At a later stage a compact gantry will be installed in the treatment area. The optics of the beam line have been designed in such a way to have a complete rotational symmetry of the beam (symmetric phase space and complete achromaticity) at the coupling point to the gantry.

A compact gantry with a diameter of only 3 to 4 m can be realised for the spot scanning method. The diameter is reduced considerably compared to other proposals by **placing the sweeper magnet before bending the beam** toward the patient (see Fig.3). The patient transporter system will be mounted directly on the gantry **eccentrically** with respect to the gantry axis. This reduces further the radius of the gantry system and acts as a counterweight for the magnets on the gantry. The rotation of the gantry must be accompanied by a counterrotation of the patient transporter system, maintaining the position of the patient horizontal at any angle of incidence of the beam.

The sweeping of the beam is performed only in the dispersion plane. This allows the gap of the magnets to be kept as small as possible. The arrangement of the scanning devices on the gantry is essentially the same as in Fig 1. The implementation of the sweeping in the beam optics of the gantry allows the design of the 90 degree magnet to be done in such a way as to displace the swept beam parallel to its direction (infinite source-to-skin distance). All three axes of scanning are in this way completely cartesian. This helps to make the treatment planning easier and reduces the skin dose.

The spot scanning method allows the addition of dose fields shaped like wedges into a single large homogeneous field. In this way it is possible to irradiate treatment volumes larger than allowed by the maximum range of scanning. This should permit us to keep the width of the pole tips of the 90 degree magnet rather small.

4. Future plans for a hospital-based proton therapy facility

Any type of accelerator (synchrotron, synchrocyclotron, sector cyclotron) can in principle be utilized for proton therapy. The relative merits of any of these solutions are quite difficult to judge at present. From the point of view of reliability and simplicity of operation a sector cyclotron should be a very attractive solution. This machine should not present any problem with respect to beam intensity, which other solutions could possibly have. The cyclotron has the best possible time structure of the beam suitable for the realisation of a beam scanning technique with three dimensional conformation. With a sector cyclotron (or synchrocyclotron) the switching on and off of the beam can be done directly at the ion source (elimination of the fast kicker magnet). This possibility is also very attractive from the point of view of patient safety during treatment. The major drawback of these accelerator types is the fixed beam energy. Propositions for constructing cyclotrons or synchrocyclotrons with 2 or more fixed energies have been formulated recently [10,11].

The possibility to vary the energy (even on a pulse by pulse base) is probably the strongest argument in favor of the Fermilab compact synchrotron [12] for the Loma Linda proton facility, which will become operational this year and will be the first hospital-based proton facility in the world.

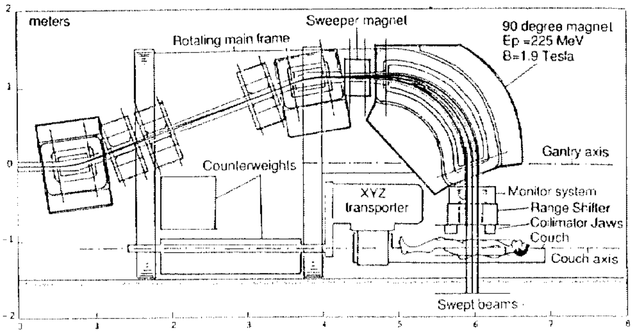

Figure 3: Schematic representation of the 360° compact gantry design for PSI.

One of the most important issues to be investigated with the new proposed beam line at PSI will be the importance in the practice of daily treatments of being free to choose the energy of the proton beam. This experience will be a major guideline for deciding on the accelerator type toward the realisation of the first hospital based facility for Switzerland.

This project is supported by a grant from the Swiss National Science Foundation (NFP18, 4018-25687).

References

[1] J.E.Munzenrider et al, Strahlentherapie 161(1985)756.

[2] S.Graffmann et al, Strahlentherapie 161(1985)764.

[3] J.M.Slater et al, Int. J. Rad. Oncol. Biol. Phys., Vo 14(1988)761.

[4] C.F.v.Essen et al, Int. J. Rad. Oncol. Biol. Phys., Vo 11(1985)217.

[5] R.Greiner et al,Muench. med. Wschr. 131(1989)652.

[6] Proton therapy project at PSI. Status report Nr 1 (June 1989). Dept. of Rad. Medicine, PSI.

[7] Proceedings of the International Heavy Particle Therapy Workshop, PSI, Sept.18 to 20,1989.

[8] H.Blattmann et al,Strahlenther. Onkol., 166(1990),45.

[9] M.Phillips et al,Dose Homogeneity ..., this conference.

[10] H.G.Blosser, East Lansing, Michigan State University, USA, private communication.

[11] Y.Jongen, PTCOG XII, Workshop on proton gantries ..,Loma Linda, Ca, USA, May 1990.

[12] F.T.Cole et al, Proc. of IEEE Particle Accelerator Conference, 1987,pp. 1985.