COMMISSIONING AND USE OF THE PSI SPOT-SCANNING ISOCENTRIC SYSTEM FOR PROTON THERAPY

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At PSI a new proton therapy facility for the treatment of deep seated tumors using a scanned proton beam is being commissioned. The facility came into operation with the treatment of veterinary patients in 1994 . We report here on the measured properties of the beam on the gantry, on the first experience with the scanning system and on the mechanical devices for the patient handling. The treatment of human patients is about to be started. The project has been somewhat delayed by a late delivery of some of the safety components, necessary for the redundancy of the control systems for the dynamic scanning.

1. Introduction

The proton therapy facility being presently realized at PSI is characterized by a number of challenging new technical developments:

1. the application of the dose by scanning a focused proton beam directly within the patient (spot scanning method - with routine three-dimensional conformation of the dose)

2. a compact isocentric gantry and

3. the optimization of patient handling (patient transporter, dedicated CT unit, X-ray devices on the gantry for patient positioning, proton radiography equipment, combined use of the CT data for treatment planning and for daily control of the patients position, Monte Carlo verification of the dose calculation algorithms etc.).

A complete description of the technical aspects of the project has been recently published in the January 1995 issue of Medical Physics. We refer here to this paper for the technical details of the facility design[1].

In the following we report on our initial experience with the isocentric gantry at PSI and on the use of the spot scanning technique.

2. Status of the PSI proton therapy facility

The installation of the proton gantry is almost complete and all devices are now in place. However, the technical equipment is not completely debugged and all the different operational procedures have still to be optimized.

The photograph presented in figure 1 shows the proton treatment room as it stands in Summer 1995. A friendly atmosphere for the future patients of the facility has been achieved with a "Japanese-like" decoration in the proton treatment room.

We are presently in the middle of the commissioning phase of the proton gantry and we are pleased that the machine is performing well and is in good agreement with the parameters of the design.

The beam was first transmitted through the gantry in Summer of 1994. During this beam period we developed the basic instrumentation for the scanning of the beam, up to the point that we were able to perform in September 1994 the first treatment of a veterinary patient (a dog) using the scanned proton beam with the gantry in the vertical position (collaboration with the Veterinary Medical Clinics of the University of Zürich, Dr. B. Kaser-Hotz).

After the winter shut down of the PSI accelerator, we continued with the treatment of animal patients with spontaneous cancer in 1995. These preliminary treatments provided extremely valuable practical experience in the use of the machine. However, most of the beam time in 1995 has been spent commissioning the whole facility, improving our dosimetric methods and installating the remaining components of the gantry.

We are now very close to being able to treat human patients. The major component missing is the software for the second computer system (the dose controller software and the related practical implementation of the double redundant control of all scanning devices) and the electronic for the third, parallel method of switching off the beam in the event of an interlock condition. Both elements are necessary for providing the safety of the treatment necessary for the application of the spot scanning technique with human patients.

We hope that these components for the safety of the treatment will be ready before October of this year, which is the last possible date for performing the first treatments with a human patient in 1995 before the winter shut-down of the PSI accelerator.

In any event, in Spring 1996 everything should be ready for starting the medical program of the new proton facility. In the following we report on the most important result of the commissioning work performed in 1995.

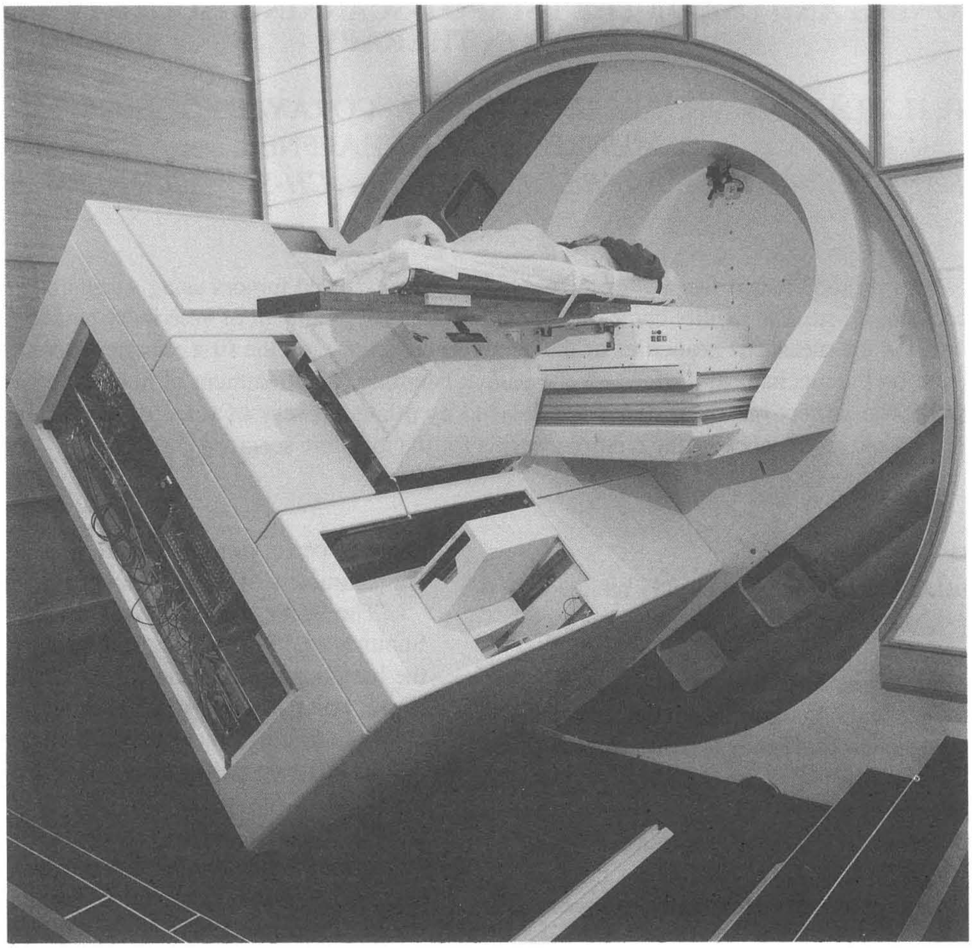


Figure 1 Photograph of the treatment room at PSI with the head of the proton gantry

3. The measured properties of the beam of the gantry

The beam used for therapy at PSI is delivered by the PSI isochronous cyclotron. A small part (5-10 μA of the 1.2 mA) is separated from the 590 MeV main proton beam using an electrostatic splitter and is brought into the nucleon hall (NA-hall) where it is then degraded in energy down below 250 MeV (using a variable stack of carbon and copper blocks). The beam is analyzed in momentum and phase space in a dedicated beam line (NA3 beam line) and is then injected into the isocentric gantry for proton therapy.

Figure 2 shows a cross section of the PSI gantry.

By the use of the splitter and of the degrader it is possible to deliver the proton beam for therapy with variable energy simultaneously to other physics experiments, including the operation of the new neutron spallation source, which is expected to go into operation at PSI in the fall of 1996. The beam for therapy will be available 4 days per weeks for about nine months per year.

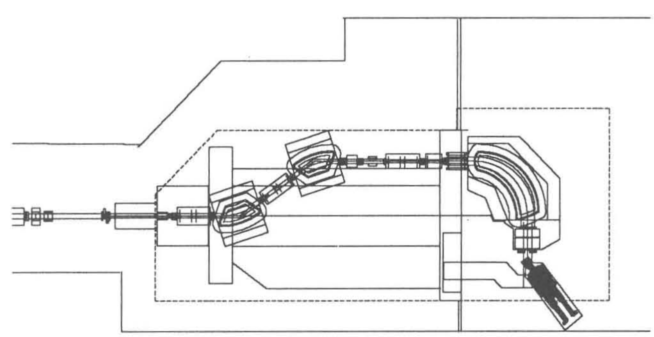


Figure 2. Cross section of the PSI isocentric gantry

The beam optics of the NA3 proton beam line and of the gantry were designed to produce a small pencil beam. The beam will be deposited directly in the patient by scanning the focused beam (see the section 4 below). The beam optics were designed to be invariant with rotation of the gantry. Both beam lines, NA3 and gantry, are therefore completely achromatics. The beam optics are described in greater details in reference[2].

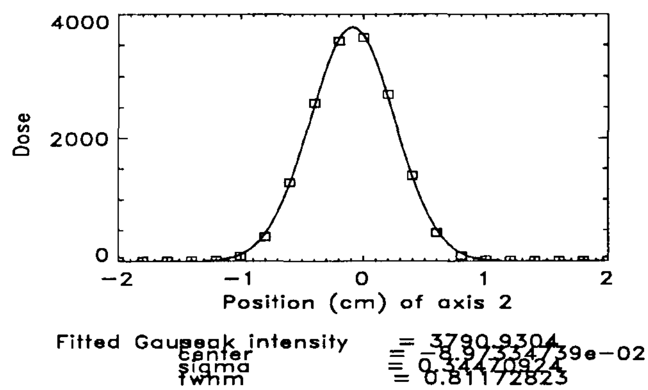


Figure 3. Beam profile in the transverse direction x

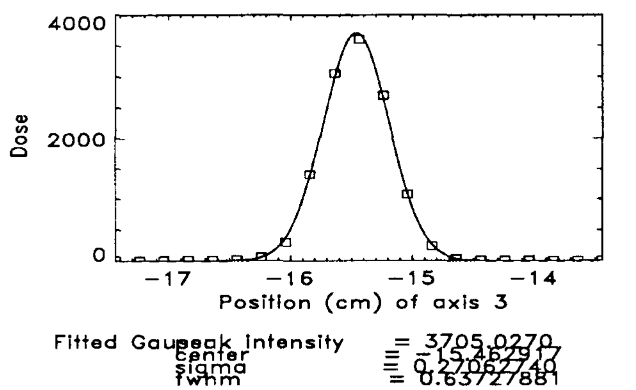


Figure 4 Beam profile in the dispersive direction

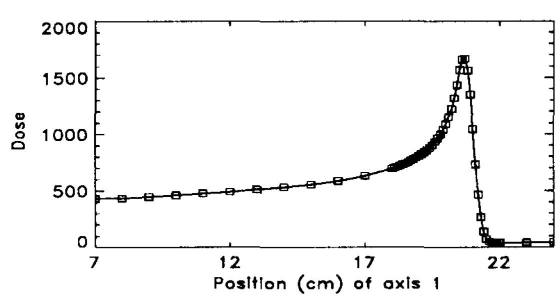


Figure 5. Depth dose distribution at 177 MeV

The properties of the beam emitted from the gantry were measured with an energy of 177 MeV. Figures 3,4 and 5 shows examples of the x, y (the transverse profiles in air) and of the z profiles (in water) of the beam, measured at the isocenter of the gantry. The size in air is 6.5 mm x 8 mm FWHM respectively. The size reflects the dimensions of a 8 mm round collimator installed at the coupling point of the NA3 beam line to the gantry.

The transverse profiles at the isocenter were measured at different gantry angles and were fitted with a Gaussian distribution (the distribution and the corresponding parameters of the fit are shown respectively as the solid line and as the text at the bottom of figures 3 and 4).

The center and the width of the profiles are plotted , as a function of the gantry angle, in figure 6 for the transverse and in figure 7 for the dispersive lateral direction of the beam.

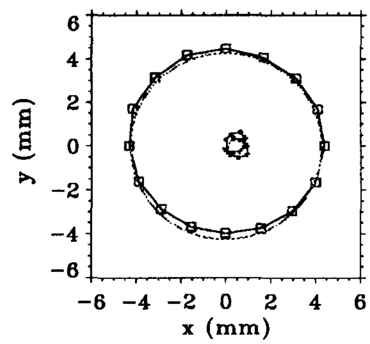


Figure 6. Isocentricity of the beam of the gantry in the non-dispersive transverse direction. The innermost trajectory of points represents the plot of the center of the beam projected on its transverse direction (in the x and y plane) as a function of the gantry angle. The external points represent the projected width of the beam (for comparison an exact circle is also shown as a dotted line).

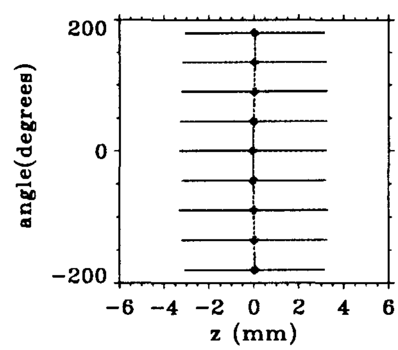


Figure 7. Plot of the center and width of the beam in the dispersive direction (z-axis) for different angles of the gantry (the vertical axis)

From both pictures we see that the beam of the PSI gantry is well centered (with an error of less than 1 mm) on the geometrical isocenter of the machine and that the width of the beam does not significantly change with gantry angle. This is a very important result, especially for the practical purpose of simplifying treatment planning. That this is not a trivial result can be understood from the fact that we are using a rather large momentum band (1.4%). If the achromatism of one of the beam lines were not well satisfied or if the emittance and acceptance of both beam lines would not match, one would quickly observe a dependence of the shape of the beam with gantry angle. These results therefore verify that in essence all the beam optics calculations originally done for the design are correct.

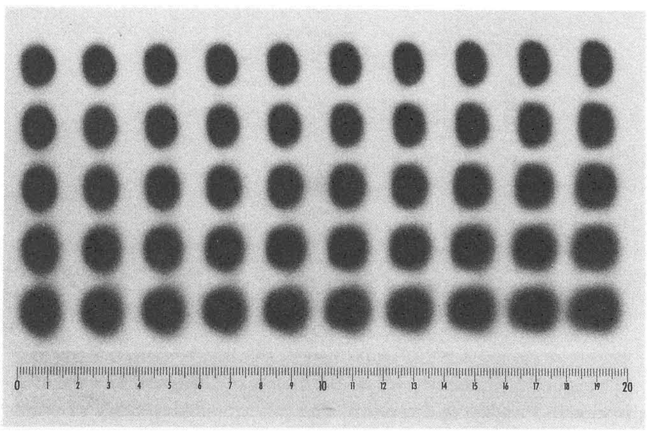


Figure 8. Exposure of a X-ray film to different proton dose spots applied as a function of the sweeper setting (along the horizontal axis) and at different depths in air (in 10 cm steps). See also text.

Another important feature of the gantry beam optics is the parallelism of the displacement of the beam as a function of the setting of the sweeper magnet. The magnetic scanning of the beam is performed using a sweeper magnet, which is located on the gantry beam line just ahead of the 90^{0} bending magnet. The poles of this magnet were designed with tilted angles and with pole curvatures in such a way to produce a displacement of the beam parallel to its direction. The parallelism of the swept beam is demonstrated by the gantry measurements of figure 8, which shows the impact of the beam on a dosimetric film for 10 different settings of the sweeper magnet (each corresponding to a beam displacement in the dispersive plane of 2 cm). The picture was taken repeatedly at 5 different distances from the nozzle (in steps of 10 cm) along the beam direction and by shifting the film laterally by 2 cm for each depth. The picture shows that the beam is shifted parallel to itself and that the beam shape at the exit of the range shifter is more or less invariant with sweeper setting. The spots usually used for the treatment are located immediately at the exit of the range shifter and correspond to the upper row of points.

The preliminary experience with the gantry indicates, that the beam optics calculations were performed correctly and that the beam on the gantry will satisfy all required criteria for an optimized scanning of the beam

4. First experience with the Beam Scanning System

The second major challenge of the project is represented by the new method of application of the dose using the spot scanning technique.

For the active scanning of the beam, the DC time structure of the beam of a cyclotron is a prerequisite.

The beam is applied at PSI using the so called "discrete spot scanning" technique. The beam is deposited as a sequence of static dose applications by applying the focused proton pencil beam directly in the patient.

Each single static irradiation with the pencil beam produces a dose distribution that is well localized in all 3 dimensions with a dose maximum at the Bragg peak position (the so-called dose "spot"). A fast kicker magnet in the NA3 beam line is used to switch on and off the beam with a time delay of less than 100 µs. A fast ionization monitor measures the dose while the beam is being applied and switches off the beam when the desired amount of dose has been deposited. The overall reaction time of both the beam monitor and the kicker magnet together has been measured to be about 150 µs. This corresponds to about 1% of the mean irradiation time (12 ms) of the spots. With these two devices it is possible to control very precisely the delivery of the dose of each single spot, despite the presence of large instabilities in the beam intensity produced mainly by the splitting of the 590 MeV proton beam. The delivery of the dose is made in this way to be independent of the quality of the beam delivered by the PSI accelerator. The almost complete decoupling of the dose delivery system from the accelerator is achieved in two steps, firstly by analyzing the momentum band and the phase space in the NA3 beam line after the degrader and secondly by controlling the number of protons in the beam with the kicker magnet.

The modification of the setting of the devices which control the position and the range of the protons in the patient is performed with the beam switched off. When all devices are ready at the settings for the next spot, the beam is switched on and the dose deposition is resumed.

The scanning of the beam is performed most often with a sweeper magnet which shifts the beam in the direction parallel to the gantry axis. The second motion is performed by introducing polyethylene plates in the beam (36 plates, each of 5 mm thickness, a plate of half thickness and foils of high Z-material which provide an optional additional scattering of the beam). The range shifter plates shift the Bragg peak in the patient in depth. The scanning along the third axis is performed by moving the patient using the patient table. The three scanning axis are orthogonal to each other and provide a complete Cartesian system of scanning. In the language of radiation therapy this means that the "source-to-skin-distance" of the PSI gantry is infinite.

The dose can be applied by choosing freely the position and the amount of dose of each spot by computer control. The sequence of spots is executed according to a data list prestored in a data file. the so called steering file. All the data are precalculated individually for each patient at the time of treatment planning.

The advantages expected from this method, as compared to the more traditional method of scattering the beam and shaping the dose using collimators, compensators and range shifter wheels, are the following:

-the distribution of the dose deposited in the patient is exactly tailored according to the 3D target shape (3D-dose conformation)

-The dose is applied completely under computer control without the need of individual hardware for shaping the dose. This could prove to be an important factor for increasing the efficiency of the utilization of the facility

-The spot scanning method is by definition a "variable modulation" technique, as opposed to the other techniques which operate with a fixed modulation of the beam range. This implies that only the very absolute minimum of protons are used in the patient vicinity, thus reducing the burden of unnecessary dose in surrounding healthy tissues

-This scanning method is an integral part of the gantry concept and is probably a necessary choice for achieving a very compact gantry design. By using the scanning method the PSI gantry currently has the smallest diameter in the world (4m).

Fig. 9 shows as an example a typical dose distribution planned for the spot scanning technique on the gantry. The underlying treatment planning system has also been developed at PSI and is a major effort in the realization of the proton therapy project.

Our first experience with the scanning system has been very satisfactory. Once the initial effort of debugging all scanning devices was accomplished, the dose appeared automatically, with the desired shape and a good homogeneity of the dose inside the target volume. This seems to indicate the method is not only very flexible but also conceptually robust.

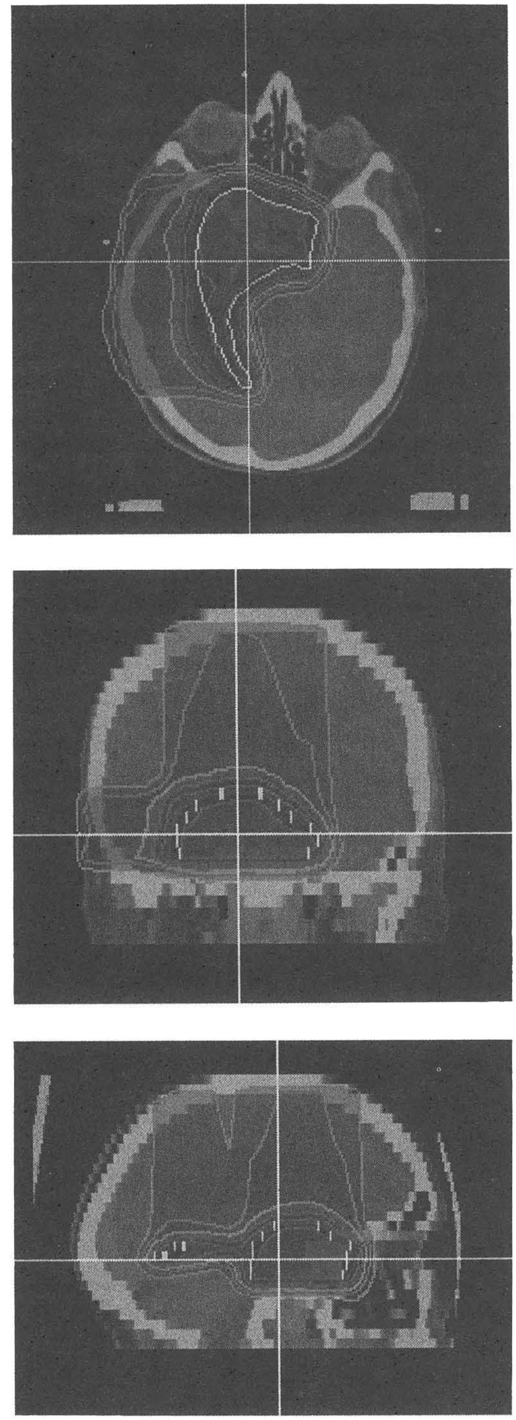


Figure 9. Example of a simulated conformal treatment of a tumor at the base of the skull using two orthogonal beam directions. Axial, frontal and sagital sections of the three-dimensional plan. The isodoses are banded in steps of 14%. The colouring of the dose is an essential feature of treatment planning which unfortunately is not possible to reproduce in this report.

The dose is calculated directly in our treatment planning system in Gy/proton using a fundamental physics model of the proton beam and the application of the beam is performed by monitoring the total number of protons in the beam. The resulting absolute dose agrees very well, at the level of a few a percents, with the dose measured with thimble ionization chambers calibrated in a Cobalt beam

The PSI treatment planning system takes into account body inhomogeneities. We have started experiments with the beam with the goal of learning about the precision of the dose especially from the point of view of controlling the proton range in the presence of body inhomogeneities. Fig 10 shows the dose distribution of a 45^{0} proton field calculated for a simulated plan in the Alderson phantom. The regular shape of the dose field is in this case intentional. The dose is calculated taking into account the irregular boundary and the bony structures of the skull. The resulting modifications of the proton range are automatically corrected in the beam scanning procedure by selecting the corresponding number of range shifter plates. Errors in the calculation are expected to show up as a change of the regular shape of the dose field. Figures 11 and 12 show two measured profiles (data points) compared with the predictions of the treatment planning algorithms. The agreement between calculation and measurement is good.

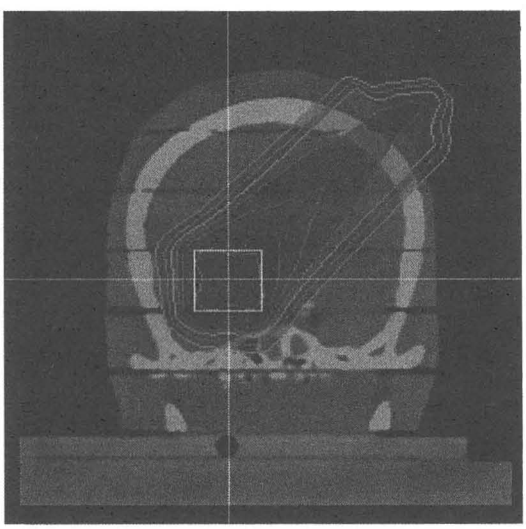
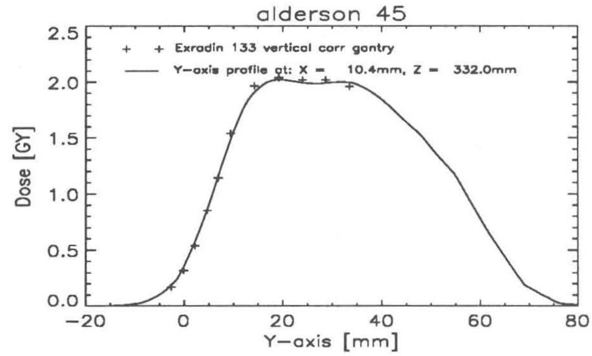


Figure 10 Simulated treatment with a 45^{0} single dose field in the Alderson phantom.

In the context of the long range goal of the project to improve the precision of the proton treatments we are working on calculating dose error estimates in the treatment planning using analytic algorithms. We have also developed to this purpose a dedicated fast Monte Carlo code to study the errors produced on the dose distribution by bones and air in body cavities, with good statistics at a position resolution equal to the pixel size of the CT matrix used for treatment planning. Another interesting development is the realization of a fast proton radiography system, to be installed on the gantry. This system is being developed by the University of Munich in collaboration with PSI.



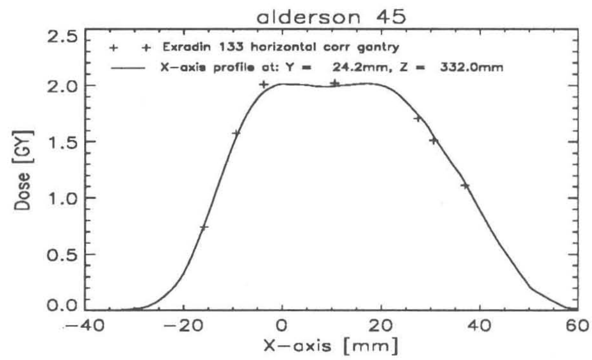


Figure 10 and 11 Calculated (line) and measured (symbols) dose profiles for the dose field of figure 10.

5. Patient Handling

Another very important new development of the PSI facility is the integration of computer tomographic (CT) equipment into the whole treatment procedure.

The patient will be treated at PSI in the supine position lying in an individual mold of rubber foam. The patient will be usually prepared for the treatment outside of the gantry room. A special trolley (figure 12) will be used for the transport of the patients immobilized in the treatment position in his couch. The patient will be moved first from the preparation room into the CT room, where he will undergo a first positioning control using scout view images taken with the CT unit. He will then be transported into the treatment room, where he will receive his proton treatment. The commercial CT table has been replaced by one developed at PSI (figure 13), which provides a coupling of the couch from the transporter onto the CT unit in the same way as this is done on the gantry (figure 12). This provides the automatic transfer of the patient's coordinates between the different locations of the treatment, namely treatment planning and positioning control with the CT and the actual irradiation on the proton gantry.

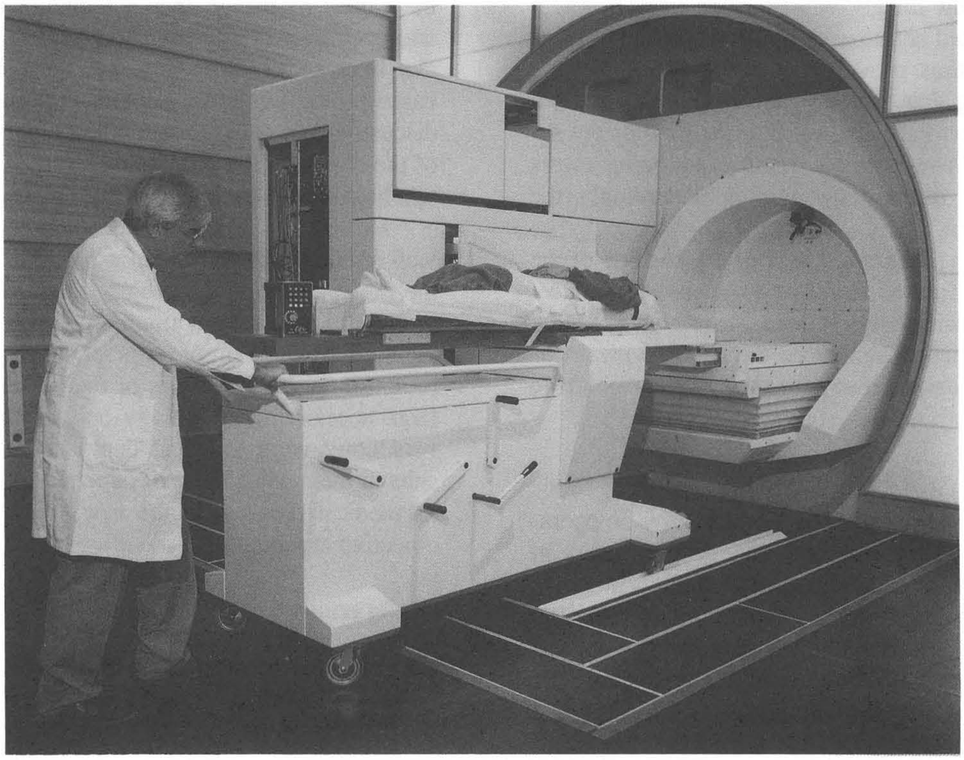


Figure 12. Transporter system used for moving the patient in his treatement position between CT unit and proton gantry.

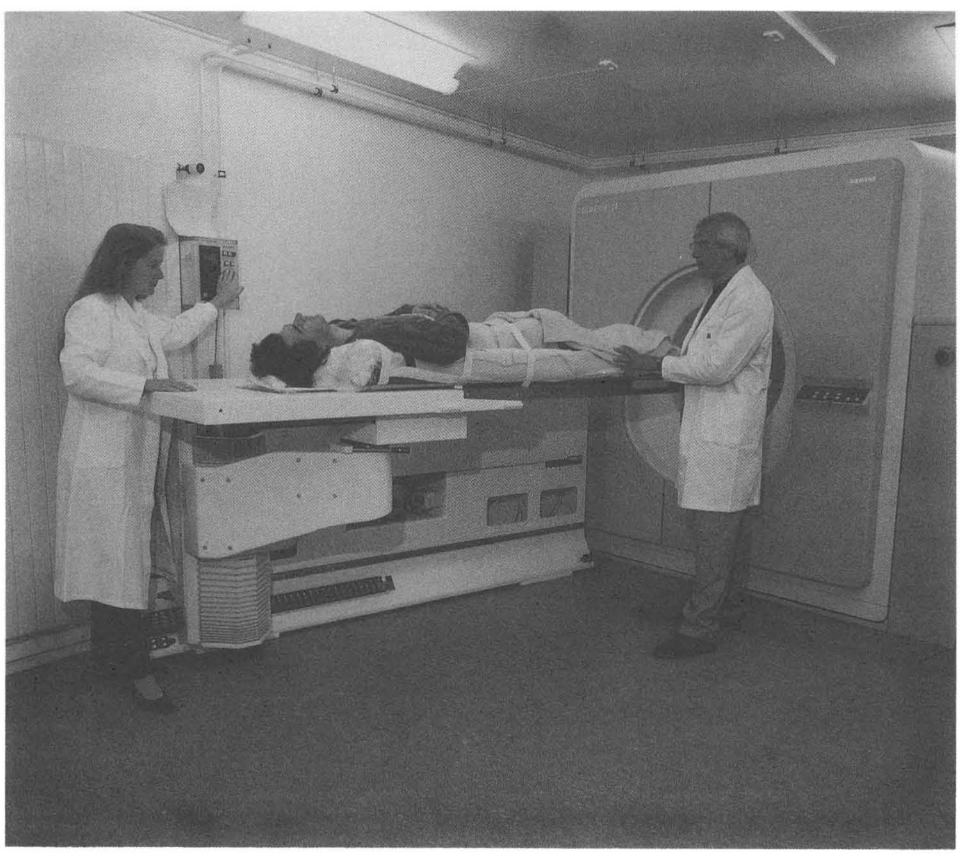


Figure 13. Modified CT unit to allow for the coupling of the patient couch on the CT and on the proton gantry

For each patient the CT will be used to provide the CT slices used for treatment planning. On this occasion reference scout view images will be taken as well. These will be then repeated before each fraction (for a total of up to 30 fractions), thus providing a direct check that the treatment planning data stored in the computer and used for steering the beam are also valid at the time of the actual treatment. Where possible small positioning errors will be corrected directly by altering accordingly the steering of the beam.

If necessary an additional check of the position of the patient can be performed directly on the gantry using retractable supports with X-ray tube and film holder. Figure 14 shows a simulated treatment on the gantry with the x-ray equipment in position ready for taking an X-ray image of the patient.

6. Conclusions

PSI is the second place in the world to have an operational isocentric proton gantry (three gantries exist at Loma Linda, which is the only place in the world where proton therapy is offered in a hospital environment). The PSI gantry presently has the smallest diameter (by about a factor of three) and is designed specifically for the spot scanning technique, which at these proton energies is a challenging new technique. By the use of the spot scanning method and of the integrated patient handling we hope to show an improved efficiency of the utilization of the gantry room and thus a reduction of the investment and operational costs per patient. These ideas are of special interest for those who are designing new hospital-based proton facilities. Another important component not discussed here is the choice of the type and also the details of the design of the accelerator. Here is where the competent help of the specialists of this conference is expected.

However, beside these technical issues, which are all well suited to be studied in a research institute like PSI, the major goal of the project should remain the task to provide to the medical community in Switzerland (and of the surrounding Europe) a practical first direct access to proton therapy. The doors of the hospitals will open to a large accelerator technology only after the delivery of a very convincing practical demonstration of superior results in the medical cure of patients. In 1996 PSI will start its medical program in the new proton facility with this objective in mind.

References

1 E.Pedroni et al, *Med. Phys.* **22**, 37 (1995)
2 E. Pedroni and H.Enge, *Med. & Biol. Eng. & Computing*, **33**, 271 (1995)

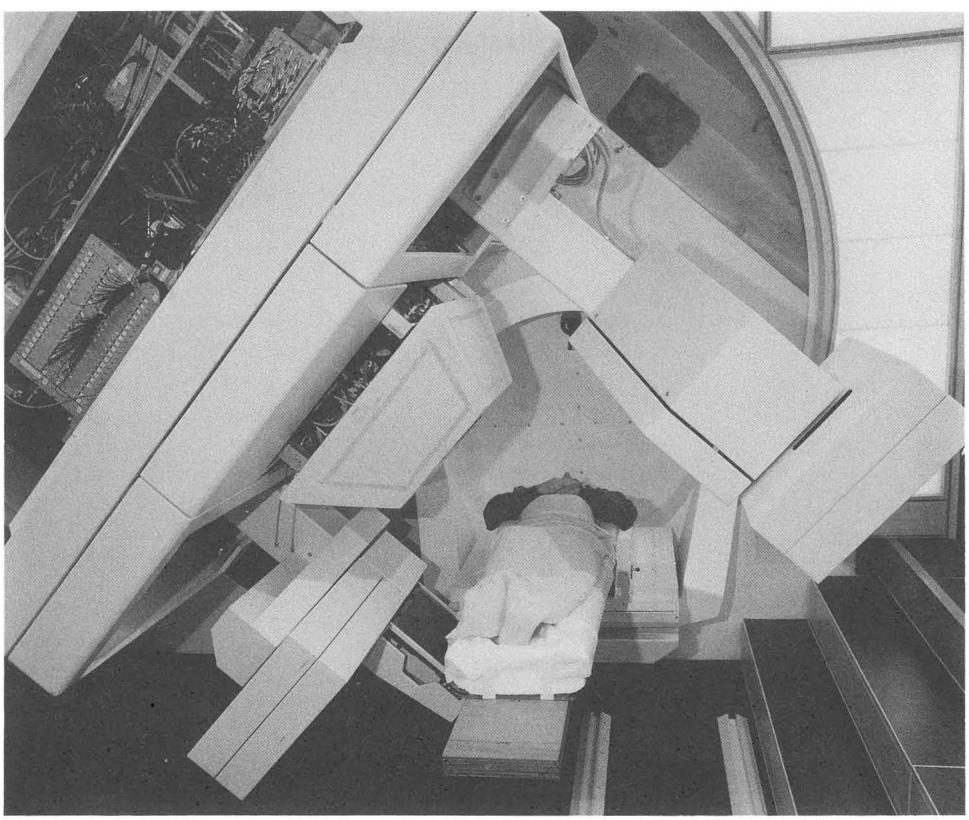


Figure 14. Removable devices for the positioning control of the patient on the proton gantry using X-ray pictures (operational) and proton radiographies (planned)