IBA PROTON PENCIL BEAM SCANNING: AN INNOVATIVE SOLUTION FOR CANCER TREATMENT

B. Marchand, D. Prieels, B. Bauvir
Ion Beam Applications s.a. (IBA)
Chemin du Cyclotron 3, B-1348 Louvain-la-Neuve, Belgium

R. Sépulchre, M. Gérard
Institut Montéfiore B28, University of Liège, Belgium

Abstract

Particles are used in medical application for cancer treatment. Radiotherapy aims to deliver a high dose in a well-defined target volume while sparing the healthy surrounding tissues. Compared to the conventional radiotherapy (X-ray), protons show superior clinical performances thanks to their inherent depth dose characteristic (Bragg peak). In proton therapy, several techniques can be used to deliver the dose into the target volume. The most auspicious method, the one that allows the best conformation with the tumor, is called "Pencil Beam Scanning". This method consists in directing lots of small pencil beam into the target in order to cover the 3D volume. IBA is developing an innovative pencil beam scanning method. The beam position is adjusted in X & Y by 2 scanning magnets while the depth depends on the beam energy. The 3D volume is divided in several slices parallel to the body surface. The dose in each slice is delivered by controlling simultaneously the beam intensity and the speed of the beam spot in the X & Y direction. The major advantage of the pencil beam scanning developed by IBA will be the pliancy in dose distribution shapes in an optimum way in term of minimizing the total treatment time.

1 INTRODUCTION

IBA Pencil Beam scanning is a method in which a proton beam spot is moved by magnetic scanning while the beam intensity is adapted simultaneously yielding finally to the desired dose distribution planned by treatment planning frame by frame (each frame corresponding to one energy selection).. The objectives will be to optimize time history evolution of the 3 manipulated variables (beam current, scanning magnet currents (X & Y)) along a pre-determined beam path in order to reach the prescribed dose in a very conformal way and within the minimum amount of time. The path planning is done with respect to the dynamic evolution and the associated constraints on the commanded variables while ensuring to reach the prescribed dose distribution within fixed tolerances.

2 IBA PENCIL BEAM SCANNING BASICS

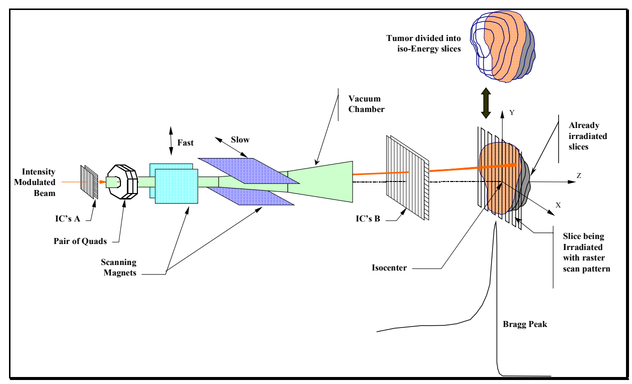


Figure 1: Nozzle Layout Principle

As shown in figure 1, the PBS nozzle itself will consist in different subsystems allowing (1) to control the beam (2) to monitor the beam and (3) to align the patient. position during the irradiation. All elements will be removable to facilitate the maintenance except the extra pair of quadrupoles and the two scanning magnets that will be considered as integral part of the nozzle frame.

Quadrupoles and vacuum chamber:

The pair of quadrupoles allows to adjust the width of the beam spot at isocenter. A theoretical study showed that, at maximum energy, we could reach a spot of 2.5 mm (one sigma). In practice, the size of the pencil beam will be adjustable during the irradiation between $\sigma = 2.5$ mm and $\sigma = 10$ mm To allow rapid changes, the quadrupoles will be laminated. To reach such small beam we will use a vacuum chamber up to minimize the scattering in air.

Scanning Magnet Power Supply:

A Scanning Magnets Power Supply of high performances is used to drive the scanning magnets that guide the beam spot into the target. This power supply consists in two fast IGBT's PWM (8kHz & 5kHz) inverters with magnet voltages "inner" regulation loops. The behavior of the actual regulation has been tested through the first measurements already made and gives quite good results in following speed trajectories. However, as it's shown on figure 2, we notice some small discrepancies in the field size accuracy.

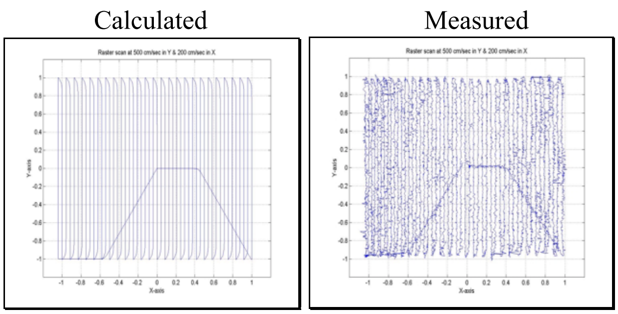


Figure 2: Geometric path of the spot

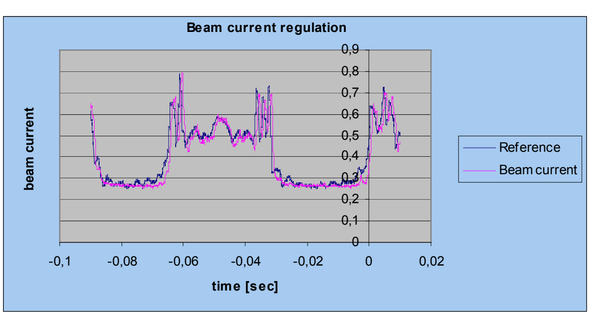
As a consequence, some improvement of the inverter regulation will be needed for proper used in pencil beam scanning. Actually, new digital "outer" regulation loops of the scanning power supply has been developed intended as positioning loops in order to improve the field size accuracy and will be tested in a near future.

Performances:

- Velocity settling time = 500 µsec.
- Fast magnet = 2000 cm/sec (Maximum speed)
- Slow magnet = 200 cm/sec (Maximum speed)

Ion Source Electronic Unit:

The beam intensity is regulated by a digital predictive controller, the Ion Source Electronic Unit (*ISEU*), driving the cyclotron source arc current and the feed-back is taken from an ionization chamber placed directly at cyclotron exit.



Performances:

- Settling time = 300 µsec.

Patient specific devices:

A major advantage of the IBA PBS is that we do not need any patient specific device (aperture and range compensator) to conform the dose distribution to the target volume. Because of the small size of the pencil beam and the thanks to the accurate control of the beam position, those expensive devices are no more necessary. Note that we will not use a multi-leaf collimator.

Range modulation:

Using a range modulator inside the nozzle is not possible because of the scattering in the modulator would open the pencil beam. Therefore, the range is adjusted upstream in the ESS (Energy Selection System) which consists in a set of absorbers followed by a pair of achromatic dipoles. Slits are used to limit the emittance and the energy spread of the beam.

The range modulation is therefore obtained by changing stepwise the whole beam line. For each step, the whole beam line can be tuned in less than 2 seconds. Accordingly, the degrader will also determine the minimum depth inside the patient. Taking into account the ESS efficiency for smallest energies will give the maximum dose rate for a given field size. The scanning surface is parallel to the body surface while irradiation will be done plane by plane.

3 FIRST EXPERIMENTAL RESULTS

The first version of the control algorithm [1] has been tested experimentally at the NPTC (NorthEast Proton-Therapy Center) in Boston on the Nozzle developed by IBA for Scattering and Wobbling treatment mode. Indeed, this Nozzle is equipped with the same scanning magnets to be used in the *PBS* Nozzle and the proton therapy equipment also includes the *ISEU* to control the Beam Intensity Modulation. Unfortunately, this Nozzle is not equipped with the "extra" quadrupoles nor vacuum chamber. As a consequence, the beam spot size used for those first tests is quite large. However, the results demonstrate how accurate we can control simultaneously the beam intensity modulation and the beam spot movement to reach the prescription.

3.1 "Raster" Scanning

The first experimental tests were done with "raster" scanning path for the spot. The figure below shows what we mean by "raster" scanning:

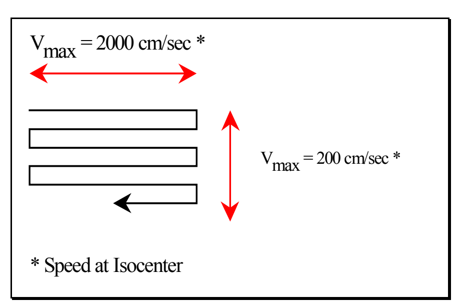


Figure 3: Raster scanning principle

In the first implementation of the control algorithm, each line is swept at constant speed so that the tracking of dose gradients is accomplished by modulation of the beam intensity only.

Constant velocity over each line:	500 cm/sec
Beam Energy:	230 MeV
Dynamic range of beam intensity modulation:	1 to 20
Beam intensity:	0 to 40 nA
Dosimetric support:	Radiographic films

3.2 *Uniform dose deposition*

The first tests realized aimed to demonstrate the excellent ability of the control algorithm to conform to any type of tumor shape and good dose distribution uniformity.

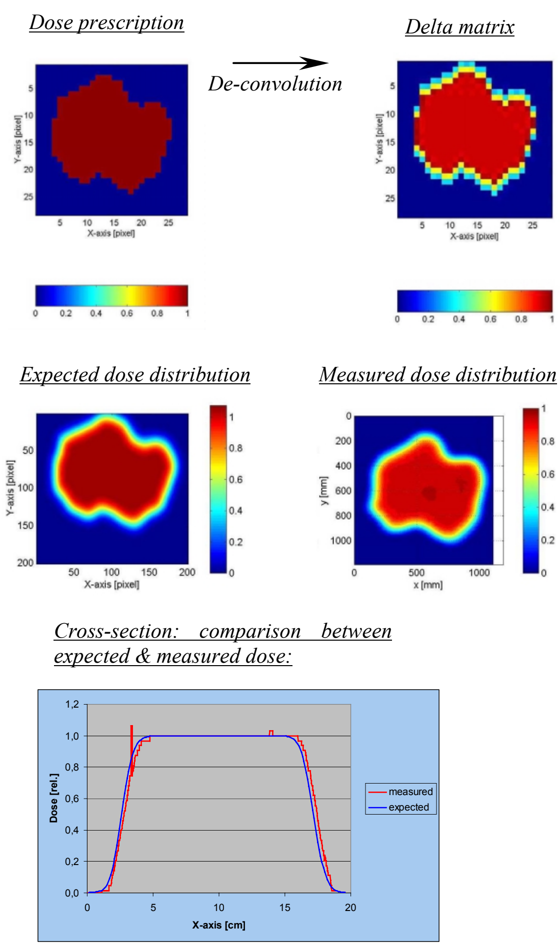


Figure 4: Uniform dose deposition

This figure speaks by itself. The uniformity is very good compared to expected and the de-convolution algorithm [1] allows reducing the lateral penumbra to around 1.2 σ. The measured sigma (σ) of the beam spot at isocenter was 10 mm. The following table summarizes the characteristics of the irradiation.

Beam spot maximum velocity:	500 cm/sec
Field size:	20 x 20 cm²
Number of passes:	2
Total irradiation time:	4 seconds

3.3 *Non-uniform distribution*

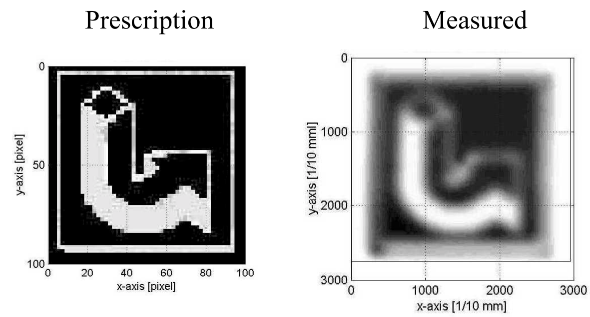


Figure 5: IBA Logo

This irradiation is really interesting because it shows how well the first version of the algorithm is able to deal very fast with dose gradient along the beam path and also shows the precision of the contour conformation. Note also that the time to irradiate this profile is very short, 2,1 second! The following table summarizes the characteristics of the irradiation.

Beam spot maximum velocity:	500 cm/sec
Field size:	25 x 25 cm²
Number of passes:	1
Total irradiation time:	2,1 seconds

4 CONCLUSION

IBA proposes an innovative pencil beam scanning that allows truly conformal therapy with 3D-intensity modulation. It allows non-homogenous distributions and faster patient treatment. No apertures or compensator will result in easier operation and lower costs. Moreover, inherently to the principle, lowest activation can be achieved since almost all protons end up in the patient.

The first experimental results are very encouraging. Future work will consist in developing the dose monitoring system and optimizing the regulation loops.

5 REFERENCES

[1] R. Sépulchre, B. Marchand, D. Prieels, B. Bauvir, M. Gérard, "Dynamic Delivery Planning in IBA Proton Pencil Beam", EPAC'2000, Vienna, June 2000.