CLINICAL PERFORMANCES OF THE DOSE DELIVERY SYSTEM AT THE ITALIAN NATIONAL CENTER FOR ONCOLOGICAL HADRONTHERAPY (CNAO)*

S. GIORDANENGO1, M. A. HOSSEINI1,2, M. DONETTI1,3, M. A. GARELLA1,3, A. ATTILI1, I. CHIRVASE2,4, M. CIOCCA3, F. MARCHETTO1, C. PERONI1,2, G. RUSSO1, R. SACCHI1,2, G. VILCHES FREIXAS3 and R. CIRIO1,2

1 Istituto Nazionale di Fisica Nucleare, via Giuria 1, 10125 Torino, Italy
E-mail: giordanengo@to.infn.it, hosseini@to.infn.it, attili@to.infn.it, chirvase@to.infn.it, fmarchetto@to.infn.it, peroni@to.infn.it, russo@to.infn.it, sacchi@to.infn.it, cirio@to.infn.it
2 Università degli studi di Torino, Dipartimento di Fisica, via Giuria 1, 10125 Torino, Italy
3 Fondazione CNAO, strada Campeggi, 27100 Pavia, Italy
E-mail: donetti@cnao.it, garella@cnao.it, ciocca@cnao.it, vilches@cnao.it
4 “Al. I. Cuza” University, Faculty of Physics, Iasi, Carol I Blvd, No. 11, 700506 Iasi, Romania

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Abstract. A dedicated Dose Delivery System (DDS) was developed to implement the modulated spot scanning technique at the Italian Hadrontherapy facility (CNAO). This is the highest conformal method in use with protons and carbon ions worldwide. The clinical 3 dimensional target is subdivided into several spots irradiated delivering a pencil beam for each spot. The right position of the beam is achieved using two orthogonal scanning magnets for X and Y displacements while the Z position of the Bragg peak (along the beam direction) is achieved by exploiting the ability of the synchrotron to provide the appropriate beam energy. Each spot of a slice is characterized by the number of particles and by the beam position which are managed and controlled by the DDS. The DDS drives the treatment spot by spot by exploiting the treatment planning data and the online measurements. The preliminary performances achieved by the system during clinical treatments are the object of this paper. The estimation of the dose delivery accuracy is evaluated comparing the prescribed values with the corresponding measured quantities. Results about dose distributions comparisons are based on γ-index and show a very good accuracy over single fields, single fractions and total treatments.

Key words: hadrontherapy, dose delivery, clinical treatments.

1. INTRODUCTION

The Italian National Center for Oncological Hadrontherapy (CNAO) is routinely treating patients by delivering protons and carbon ions with the

modulated spot scanning technique [1, 2]. This highly conformal dose delivery method subdivides the target volume into several layers orthogonal to beam direction; each layer, named slice, is irradiated by hundreds of pencil beams, which must be driven in the right position and controlled in real-time. Each spot of a slice is characterized by the number of particles and by the beam position prescribed by a treatment planning system (TPS). The task of the Dose Delivery System (DDS) is to manage the treatment spot by spot in order to follow the TPS prescriptions; this is achieved by exploiting the online measurements of the delivered number of particles and of the pencil beams positions.

The CNAO therapy system [3] is summarized in the first part of this paper together with the description of some DDS features and operations performed during a treatment delivery. A sketch of the main elements used to deliver and overlap pencil beams on target with the active scanning method is designed in Fig. 1.

The measure of the accuracy with which the fields are delivered with modulated spot scanning technique has to be performed during commissioning [4]. Additionally the DDS output data can be used for a daily check of the dose delivery stability. The analysis of the data collected during the first 10 months of clinical operation is described. The results and performances presented are related to the first treatment room in operation since September 2011 with proton beams. The study of the delivered dose distribution based on the DDS data is a work in progress and some preliminary comparisons with the TPS prescription, based on $\gamma$-index [5], are presented.

2. THE CNAO SYSTEM TO TREAT WITH THE MODULATED SPOT SCANNING TECHNIQUE

2.1. ACCELERATOR

The CNAO accelerator is a synchrotron designed to accelerate protons to a discrete set of energies between 60 MeV and 250 MeV or carbon ions between 120 MeV/u and 400 MeV/u. The set of energies allow steps of 2 mm in water along the longitudinal direction. The beam delivery time structure is subdivided in cycles characterized by spill time (about 1 s) and inter-spill of about 4 s. The maximum beam intensity ($10^{10}$ protons and $4\times10^9$ carbon ions) allows the delivery of 2 Gy in about 1 minute.

2.2. SCANNING SYSTEM

The scanning system consists of two identical dipole magnets for horizontal and vertical beam deflections located at distances ranging between 4.7 and 6.8 m upstream of the isocenter [6]. Downstream the magnets, the monitor chambers of
the DDS measure in real time the beam fluence and position. When the number of particles for a given spot has reached the planned one, the DDS sets the currents corresponding to the next spot position to the scanning magnets power supplies for shifting the beam. The appropriate current values are determined by the DDS from the beam positions specified by the TPS.

2.3. DOSE DELIVERY SYSTEM

The Dose Delivery System in use at CNAO has been designed and built by the CNAO Foundation with the Istituto Nazionale di Fisica Nucleare (INFN) and University of Torino.

It was designed to measure and control in real-time during the treatment delivery the position of the beam and the number of deposited particles. In addition to the scanning magnets, the DDS acts on the chopper to stop the delivery at the end of each slice and to pause the delivery when the distance between two spots is large to avoid too large doses delivered along the path.

![Fig. 1 – The sketch of the synchrotron ring and scanning magnets, a scheme of the beam monitors sequence and a design of pencil beams overlapped to irradiate the spots of a slice.](image)

The main monitors used by the DDS are four parallel ionization chambers [7] organized in two separate boxes placed close to the exit window of the beam (Fig. 1). Two chambers with integral anodes measure the fluence of the beam and two chambers with anodes segmented in strips measure the projection of the beam position and beam width along the transversal directions (X and Y). Additionally a pixel chamber is available for redundancy.
The DDS is interfaced with several CNAO subsystems like the Supervision system, the Accelerator Timing system, the Chopper, the Patient Interlock system, the Treatment Console and the general and local control rooms.

The data acquisition is based on 2 National Instrument PXI crates equipped with 15 NI PXI boards (FPGAs, memories, digital input-output and Ethernet boards) and 4 custom PXI interface modules. LabVIEW Real-Time OS runs on the PXI controllers but, for safety, during the delivery of the beam the treatment management is performed by the FPGAs only in a complete standalone mode.

3. DOSE DELIVERY INPUT AND OUTPUT DATA COMPARISON

During the patient positioning procedure the treatment data computed by the TPS and specified in terms of particles per spot and spot positions (mm) at the plane of the isocenter are sent to the Dose Delivery controller as a text file. At the end of each treatment delivery, the data acquired by the DDS are available to create the required Treatment record or can be used directly for the off-line analysis. These data are stored in a binary file and contain for each spot the measured positions in the strip chambers and the corresponding monitor counts, one count corresponding to 200 fC of ionization charge released in the gap of the chamber.

Before the treatment starts, the TPS data need to be converted to number of monitor counts, scanning magnet currents (in A) and position in strips units at the plane of the strip chambers. The reversed conversion is later applied to the DD measurements to produce the treatment record file which allows a direct comparison with TPS prescriptions.

Fig. 2 shows the three data conversion made by the DDS for each treatment before and after the delivery.

Part of these files, corresponding to 17 patients and 1365 fields treated with protons between January and October 2012, have been analyzed. The range of values for parameters which characterize the delivery of these fields are listed in the Table 1.
Table 1
Minimum and maximum values of the number of total fields, slices, spills, spots, spots per slice, prescribed particles and energy used among the 17 patients taken into account in the analysis

<table>
<thead>
<tr>
<th>Total fields per patient (min-max)</th>
<th>Total slices per patient (min-max)</th>
<th>Total spills per patient (min-max)</th>
<th>Total spots per field (min-max)</th>
<th>Spots/slice (min-max)</th>
<th>Prescribed particles per field (min-max)</th>
<th>E(MeV/u) (min-max)</th>
</tr>
</thead>
</table>

3.1. BEAM POSITION ACCURACY

The measured spot positions have to be distributed as close as possible the planned ones. This condition is always verified. For example, as seen in Fig. 3 the spots measured in the different fractions are around the requested location, identified by a black dot. To compare the strip chamber measurements with the TPS positions the conversion from nozzle coordinates to isocenter is also performed.

![Fig. 3 – Spot positions for 20 identical fractions (red dots) and the correspondent required positions (black dots).](image)

The precision achieved in the delivery for the X (horizontal) and Y (vertical) position of the spots is presented in Fig. 4 and Fig. 5 respectively. The difference between the measured and required beam positions at the isocenter have been evaluated for each field in each day through the measurements performed by the DDS in the nozzle.
Fig. 4 – Percentage of spots within three different position tolerance thresholds (< 0.5 mm blue dots, < 1 mm red dots, < 1.5 mm green dots) for the horizontal coordinate X. Each point corresponds to a single field, and more than a single field is sometimes present in each day.

The percentage of spots satisfying three different position tolerance thresholds (< 0.5 mm blue dots, < 1 mm red dots, < 1.5 mm green dots) are shown in the plots as a function of the day. Each point corresponds to a single field and for each day different fields are sometimes present. It can be observed from the figures that the spots are delivered with better precision along Y than along X, as expected considering that the beam deflection in the ring and the beam extraction occurs in the horizontal plane.

Figure 4 shows a worse precision in February and in some days of May. The QA measurements performed daily at the isocenter showed a similar effect; however the results were still satisfying the QA tolerances.

Fig. 5 – Percentage of spots within three different position tolerance thresholds (< 0.5 mm blue dots, < 1 mm red dots, < 1.5 mm green dots) for the vertical coordinate Y. Each point corresponds to a single field, and more than a single field is sometimes present in each day.

3.2. BEAM FLUENCE ACCURACY

The amount of charge released from the particles interaction with the gas is measured spot by spot by the two integral chambers, where the charge quantum corresponding to each count is 200 fC. This charge is related to the number of protons delivered to the patient through a conversion coefficient which depends on
the beam energy and is determined by dosimetric procedures [8]. Therefore the number of particles delivered in each spot can be determined and compared to the TPS prescriptions. However, before applying this conversion, few corrections have to be considered.

1) The system is designed such that whenever one of the two chambers reaches the prescribed number of counts specified for the chamber, the delivery of the spot is terminated and the beam is moved to the following spot. The second chamber is used as a safety monitor and the prescribed counts correspond to 10% more particles than the first chamber. However it may happen that the second chamber reaches the prescribed counts before the first chamber because of the effect of noise; for these spots 10% more particles than the prescribed are therefore delivered.

2) Dark noise between spills affects the dose delivered to the first spot of each spill; a technique has been developed to determine the over or under dose which is later added to the measurement.

3) The chopper is the device used to stop the beam delivery in a short time. However for about 100÷200 µs particles are delivered and the amount of exceeded counts are evaluated off-line.

The relative error of particles delivered (%err) for each spot is evaluated and the percentages of spots within three tolerances (< 0.5%err blue dots, < 1%err red dots, < 2.5%err green dots) are shown as a function of the day in Fig. 6. Each point corresponds to a single field, and more than a single field is present in each day.

![Figure 6](image)

Fig. 6 – Percentage of spots with relative error of particles delivered (%err) for each spot within three tolerances (< 0.5%err blue dots, < 1%err red dots, < 2.5%err green dots). Each point corresponds to a single field, and more than a single field is present in each day.

The relative differences between required and delivered particles are within 2.5% for over 98% of the spots in all the fields, the deviations being related to the three effects listed before.

### 3.3. DOSE DISTRIBUTIONS COMPARISON

To assess the effect of DDS uncertainties we developed a method using an independent TPS which allows to compute the dose distributions from a list of spot
positions and number of protons. The comparison between the dose obtained with prescribed spot characteristics and the dose computed with the measured quantities has been performed with γ-index maps in a grid 1x1 mm². The commercial software (OmniPro I³mRT 1.7, by courtesy of IBA) has been used to analyze single field accuracy and reproducibility.

The results presented here are related to one patient treated in June 2012. The γ-index maps obtained for one field of the first fraction on a central transversal slice are shown in Fig. 7. The 100% of points satisfy the 3%/3mm criteria (Fig. 7a) and almost 97% of points satisfy the 2%/2mm criteria (Fig. 7b).

![Fig. 7 – γ-index maps obtained for one field on a central transversal slice. The red points have the γ-index > 1. 3%/3mm criteria has been used for the plot a which shows a 100% of passing rate and 2%/2mm criteria has been used for the plot b with almost 97% of passing rate.](image)

The DDS reproducibility has been estimated using the reproducibility of the γ-index of the same slice shown in Fig. 7. The field considered has been delivered 24 times and the γ-index has been evaluated for each fraction with both the tolerances. The result is shown in Fig. 8 where good stability with 3%/3mm criteria where almost 100% of passing rate is always obtained whereas using the more stringent 2%/2mm criteria the passing rate is always larger than 90%.

![Fig. 8 – γ-index reproducibility using 3%/3mm and 2%/2mm criteria for one slice of one field delivered for 24 days.](image)
4. CONCLUSIONS

The Dose Delivery system of CNAO has the crucial task of precisely deliver the dose according to the prescriptions of the TPS. The output files produced by the system at each treatment allow to check the positions and the number of particles delivered in each spot. The analysis of the data collected in the first 10 months of clinical operation show that in over 95% of the spots the 1% tolerance in number of particles delivered was achieved, with little dependence on time. The large majority of spot positions were found to follow the prescription within 1 mm tolerance; here a dependence on time was observed which is related to the tuning operations on the accelerator. The analysis of the impact on the dose delivered is in progress and the preliminary results based on γ-index show a very good accuracy over single fields.

REFERENCES