AN AUTOMATIC BEAM CHARACTERIZATION INSTRUMENT FOR PROTON THERAPY APPLICATIONS

Paolo Cirrone+, Giacomo Cuttone+, Carlo De Martinis* , Dario Giove*, Marco Mauri*

*+INFN-LNS-Catania , *INFN-Milan and University of Milan*

Abstract

The characterization in the transverse plane of the beam is a fundamental step in the design of a proton therapy facility. In this paper we will describe an automatic system able to measure the transverse profiles of the proton beam used in the Catana facility at LNS-Catania. The system has been designed as an autonomous equipment able to acquire optical images of the beam (after an interaction with a converter) and to elaborate them to extract the relevant parameters. The equipment may be interfaced to the rest of the control system of the facility and to the operator interface to provide high level control and monitoring tools. Operational experience will be discussed and the results so far obtained will be outlined.

INTRODUCTION

At Laboratori Nazionali del Sud _ Istituto Nazionale di Fisica Nucleare of Catania, Italy a facility employing 62 AMeV proton beams accelerated by a superconducting cyclotron, for the radiotherapeutic treatment of ocular diseases (like choroidal melanoma, iris melanoma and macular degeneration) is active since march 2002 [1].

The good results obtained in terms of treatment accuracy are reached thanks to the frequent, reproducible and precise dosimetric checks on both transversal and depth dose proton beams distributions. All the checks are carried out using several kinds of radiation detectors like ion chambers, silicon diodes, photodiodes, thermoluminescence dosimeters (TLD), radiographic and radiochromic films.

The experience gained during the first year of operation of the Catana facility has shown that one of the major drawbacks of the monitoring systems above recalled is the time needed to characterize the beam. A complete set of measurements takes up to 30 minutes and the detectors have to be calibrated using the beam as a primary tool. A reduction in the amount of time requested by the procedure, which will result in a better use of the beam time, and the possibility to use a detector that may be calibrated in a laboratory test bench were the two starting points of our research. We take as a reference the work developed by some of us in the past years using scintillating screens and image acquisition and processing techniques in beam line diagnostics.

The system that we started to investigate was devoted to the dosimetric setting of a therapeutic hadron beam before each patient treatment. The purpose of the application was the real time reconstruction of the lateral dose distribution and the evaluation of the beam quality parameters.

The basic scheme consisted of a scintillating screen coupled with a camera which collects the fluorescence light output produced in the screen by the ionizing radiation. The acquisition and processing time required by this system must be less than 1 minute. Obviously the system has to guarantee the same accuracy and reproducibility of the routine dosimeters.

Efforts were initially concentrated on the research of the most suitable scintillating material, on the image acquisition and processing basic components and on the choice of the experimental set up (geometrical configuration of employed objects).

COMPONENTS AND METHODS

Measurement Set Up

The measurement set up was conceived as a self consistent mechanical structure which holds the diagnostic system and which can be easily inserted and removed along the therapeutic beam line. The positioning of the mechanical bench was guaranteed since it was referenced to fixed dowels in the beam line. The possibility to remove the instruments after the beam characterization allowed to avoid any kind of trouble due to the effects of the radiation on the electronics components.

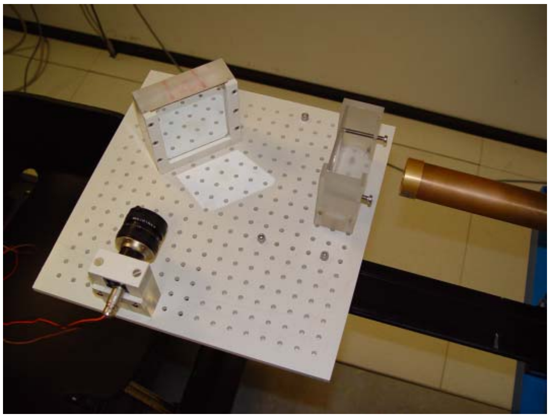

Fig. 1 Optical test setup

The geometrical constrains due to the positioning of different components along the beam line result in the following configuration. The scintillating screen is placed at the isocenter with its surface perpendicular to the proton beam axis. Behind the scintillator, at a distance of 18 cm, a mirror is positioned. It forms a 45° angle with both the proton beam and the camera axis. The role of the mirror is to reflect the light coming from the scintillator in the direction perpendicular to the beam axis. In this way the fluorescent light is collected by the camera, placed at a distance of 16 cm from the mirror.

Scintillating materials

The therapeutic beam of the Catana facility has a current of the order of 1-10 nA and a transverse diameter of the order of 38 mm (the maximum allowed disuniformity is of the order of 5% or less).

The very low current density was the main difference in the design of the system with respect to more usual beam transport line video diagnostics. Such a feature reflects in the need to deeply investigate the better available material to be used as a converter.

Three kinds of inorganic and organic scintillating materials have been tested:

1) doped alumina screens (Al_2O_3Cr, inorganic) round shaped with a diameter of 45 mm and thicknes of 1 and 2 mm;

2) 70 x 70 mm square screens of CsI(Tl) (inorganic) with a thickness of 1 and 2 mm;

3) plastic scintillating screens (BC400, organic) by Saint Gobain (Crystals & Detectors), round shaped with a diameter of 50 mm and a thickness of 2 mm.

All the samples were tested on the beam line of interest to check their properties. The first two materials proved inadequate for our purposes. Alumina showed lacking in light efficiency, yielding an output signal comparable with the system intrinsic noise. CsI(Tl) exhibited the highest light efficiency, but the response was really non homogeneous. This feature makes it unsuitable for a system conceived to measure dose distributions with high accuracy. On the other hand, BC400 showed to be the most suitable, representing the best compromise between a sufficient light yield and a great homogeneity in response. This last feature revealed to be almost equivalent to that of conventional systems like silicon diodes or radiochromic and radiographic films. The BC400 was chosen as the best scintillating material for our purposes.

Image Acquisition and Processing

The choice of the basic elements for the image acquisition and processing was carried out in two steps. At the beginning we just want to have a very flexible yet powerful system able to perform the tasks required and to allow us to gain experience with the particular operational regime above discussed. We did not look for the performance optimization of the single components but we chose to investigate the feasibility of the whole system.

We adopted a well established technology based on an analog interline CCD camera (Teli CS8620Ci, with 768x494 active pixels and 525 scanning lines, 60 dB S/N) with a good minimum sensitivity of 0.2 lux to address the low optical budget. The optic was a very high relative aperture Schneider Xenon 0.95/17 C lens. The image was digitized by a monochromatic 10 bits analog frame grabber (National Instruments PCI-1409).

The image acquisition and processing was implemented as a LabVIEW application using a PC under Window 2000 as the working platform. The PC was installed outside of the treatment room and the graphical interface of the LabVIEW application works as a measurement tool and as the operator front panel.

The geometry of the measurement set up along with the optical components above discussed result in a geometrical calibration factor of 0.112 mm/pixel.

To characterize the behaviour of the instrument we performed a measure of the Modulation Transfer Function (MTF) as a function of the spatial resolution [2]. The measure was carried out in a laboratory test bench using standard references (USAF 1951 lens test chart). A value of 0.3 for the MTF results in a spatial resolution of 2.22lp/mm, that is in well agreement with the expected resolution obtainable starting from the quoted geometrical calibration. The measure of the MTF curves was performed in a high contract regime. We were able to double the contrast of each acquired image through a background subtraction process. Such a process allows to remove unwanted background light from the image under analysis.

The signal to noise ratio of the whole optical chain was measured as a function of the square root of the number of averaged images. The value obtained was in good agreement with the theory and this confirms that the noise was mainly random.

The LabVIEW application allows to perform all of these tasks (background subtraction, noise reduction) in an automatic way relieving the operator by the duty to handle these details while he is doing beam quality parameter measurements.

EXPERIMENTAL RESULTS

Fig 2 shows lateral dose distributions obtained during tests carried out on the beam, compared with those resulting from a routine system based on a silicon diode. In Table 1 the values of beam quality parameters of both systems are reported.

	Radiation Field (mm)	Field Ratio (%)	Lateral Penumbra sx (mm)	Lateral Penumbra dx (mm)
CCD camera	25.88	0.90	1.50	1.50
Diode	25.97	0.91	1.46	1.48
Diff. %	-0.38	-0.86	2.75	1.12

Table 1 Measured Beam Quality Parameters

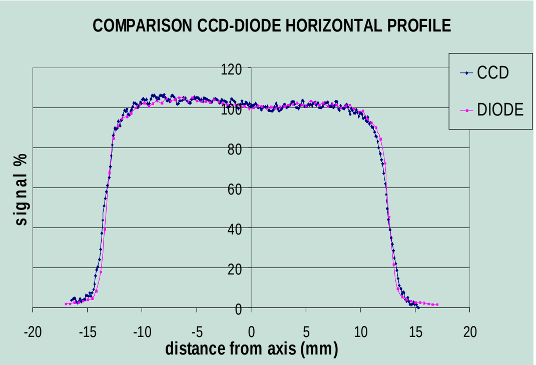

Fig. 2 Measured Beam Profiles Comparison

The results prove that the system meets the design requirement in terms of measurement accuracy. The profiles are shown on the application interface during the beam tuning and this feature greatly improves the accuracy of the process itself.

Preliminary measurements were carried out to evaluate the relation between the optical signal and the dose rate (Gy/min) delivered by the beam. The results showed that the relation is quite linear.

FINAL DESIGN

The positive experience gained during nearly one year of operation of the instrument allows us to carry out the second and final step in the design of the image acquisition and processing system.

The availability of new families of CCD and CMOS based digital cameras based on the Firewire (IEEE 1394) communication channel, with active pixel areas up to 1024 x 768 and at a cost similar to the analog ones, suggests us to move toward a complete digital approach. The S/N figure available is higher and the architecture of these cameras provides facilities, as the software control of the exposure time, which results in a better dynamic range of operation.

Fig. 3 Embedded Real Time Vision System

Embedded computers running real time kernels and packaged in an industrial way (extended temperature range, low voltage supply, no fans, etc.) overcome all the drawbacks, in terms of safety and performance, due to the use of a general purpose PC running standard Windows operating system.

During 2004 National Instruments has introduced a compact vision system (CVS-1455) design for applications based on Firewire cameras (Fig. 3). The system is based on LabVIEW Real Time and the absence of conventional mass storage device makes it attractive as a reference for an embedded instrument. The processor provides nearly 1400 MIPS of computing power and 128 Mbytes of non-volatile memory are available for code and local image storage. Image acquisition can be performed at rates up to 100 frames per second. 29 digital I/O lines are available to read status conditions and to set actions.

All the features above discussed, along with the possibility to reuse parts of the software so far developed, make the CVS-1455 an ideal platform for the image acquisition and processing system. The system presents an embedded 100 Mbit Ethernet interface which allows to integrate it in the general context of the Catana control system. We developed an embedded WEB server which provides a graphical interface useful for beam line operators and for medical physicists. Images, along with beam profiles and dose distributions, are available at an update rate of 1 second. An embedded VGA interface provides the capability to show in real time the images acquired along with an overlay plane devoted to computed parameters. The VGA signal may be distributed in the facility using optical media converters and signal splitters.

The final design of the whole system has been completed along with the new version of the embedded software. Optical performances are in excess of those above reported and tests are undergoing on the beam line.

CONCLUSIONS

A real time monitoring system of a radiotherapeutic proton beam has been designed, tested and its performance reported in this paper. Experimental results proved that its accuracy is very close to that of existing dosimetric devices. The design of the system has been evolved toward an embedded automatic vision based instrument.

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