FAST RASTER SCANNING SYSTEM FOR HIMAC NEW TREATMENT FACILITY

T. Furukawa #, T. Inaniwa, S. Sato, T. Shirai, Y. Takei, E. Takeshita, K. Mizushima, Y. Iwata, T. Himukai, S. Mori, S. Fukuda, S. Minohara, T. Murakami and K. Noda
National Institute of Radiological Sciences, Chiba, JAPAN

Abstract

A new treatment facility project, as an extension of the existing HIMAC facility, has been initiated for the further development of carbon-ion therapy in NIRS. The challenge of this project is to realize treatment of a moving target by scanning irradiation. In order to realize this by rescanning with gating within an acceptable irradiation time, the development of a fast scanning system is required. To test the fast rescanning irradiation and to verify the design, a new scanning irradiation system was installed into existing HIMAC experiment course. The beam test of the fast scanning system was successfully carried out. In this paper, the performance of the fast scanning was demonstrated.

INTRODUCTION

At the HIMAC, more than 5000 patients have been successfully treated by carbon beams since 1994. To make optimal use of these characteristics and to achieve accurate treatment, three-dimensional (3D) pencil beam scanning [1-3] is one of the sophisticated techniques in use. For implementation of this irradiation technique, at HIMAC a project [4] to construct a new treatment facility was initiated. The challenge of this project is to realize treatment of a moving target by scanning irradiation, because pencil beam scanning is more sensitive to organ motions compared with conventional broad-beam irradiation. A design study of the scanning system had been in progress since 2006. Our approach [5] is a combination of the rescanning technique and the gated irradiation method. One of the most important features of the system is fast scanning to realize moving target irradiation with a relatively large number of rescans within an acceptable irradiation time.

As a result of the conceptual design study [5], we decided to employ the hybrid raster scanning method developed at GSI [3] considering the beam characteristics of the HIMAC synchrotron for the realization of the fast scanning. In order to demonstrate the fast scanning performance and to verify the validity of the design before the machine installation into the new treatment facility, we need to test the system with the HIMAC beam. In parallel with the building construction of the HIMAC new treatment facility, therefore, the scanning system was constructed and installed in the physics experiment course (PH1) of HIMAC in December 2008, as shown in Fig. 1. The beam test was carried out from December 2008 to February 2010. As a result, we verified that the beam delivery system can produce an accurate 3D dose distribution for the target volume in combination with the planning software. Further, we verified that the system has a sufficiently fast scan speed to realize the rescanning technique with gating within a few minutes.

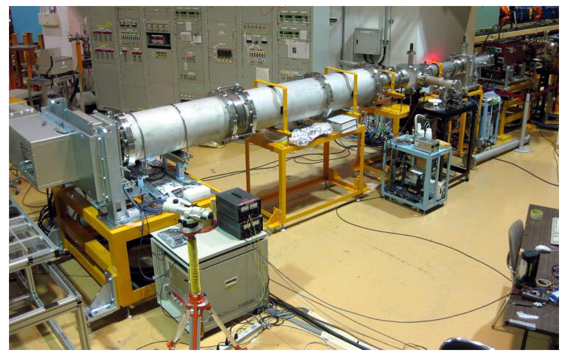

Figure 1: Photograph of the fast raster scanning system.

FAST SCANNING SYSTEM

Layout of Devices

The raster scanning irradiation system is around 9 m long between the last quadrupole magnet and the iso-center. The distances from both scanning magnets to the iso-center are set to 8.4 and 7.6 m, respectively. After the vacuum window located 1.3 m upstream of the iso-center, flux monitors, a position monitor, a ridge filter, and a range shifter are placed. Details of these components are described below.

Fast Scanning Magnet and its Power Supply

Specifications of the scanning magnets and their power supply are summarized in Table 1. The gap of the magnets and the good field region are defined based on the beam envelope calculation. The maximum magnetic field of both magnets is designed to be less than 0.3 T to decrease the eddy current and the iron losses. In addition, the silicon-steel lamination thickness of 0.35 mm was employed. Vacuum ducts in the scanning magnets are made of FRP to suppress the eddy current. In order to check the eddy current effect especially for the magnet edge, measurement of the temperature rise was carried out. Figures 2 show the picture of the horizontal and vertical scanning magnets and the typical result of the temperature rise measurement for the horizontal scanning magnet. The temperature rise was not severe, even when operating at the maximum field and repetition rate.

In the power supply, IGBT units and FET units are employed, and separated functionally. The IGBT units are used to change the current fast, and the FET units are used to keep the current constant with the PID feedback control. The fast control of the IGBT is the most crucial issue of this power supply. The switching timing precision of around 300 ns is necessary to suppress over/under shoot. As shown in Fig. 3, the overshoot is successfully suppressed within 0.5 A corresponding to the beam-position shift of 0.2 mm.

Table 1: Specifications of scanning magnets and their power supply

	unit	SMx	SMy
Deflection angle	mrad	±18	±21
Magnet gap width	mm	40	82
Effective length	mm	393.6	681.2
Pole length	mm	360	618
Pole width	mm	90	140
Max. field strength	T	0.286	0.190
Num. of coil-turns	turns/pole	12	15
Coil resistance	mΩ	5.6	10.3
Coil inductance	mH	0.94	2.02
Max. current	A	±410	±440
Max. voltage	V	420	460
Scan speed	mm/ms	> 100	> 50

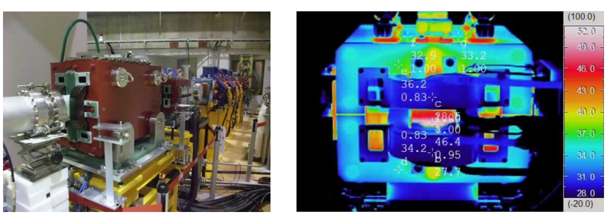
Figure 2: Picture of the scanning magnets and the result of the temperature-rise measurement.

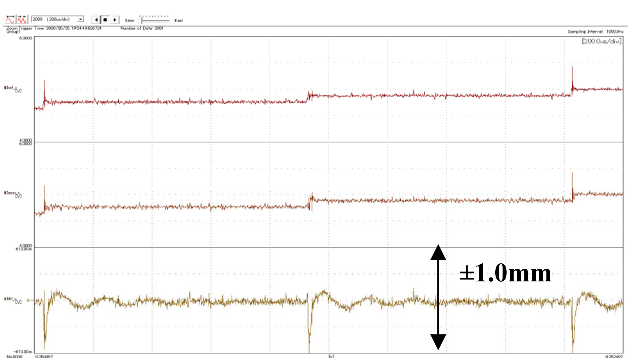

Figure 3: Oscilloscope display in the power supply test. From the upper trace, the reference current, the measured current and the measured deviation. Time scale is 200 μs/division.

Beam Monitors

The beam monitoring is one of the most important components in the scanning delivery. In order to measure and control the dose of each spot, two flux monitors (main and sub) and a beam position monitor were placed. These monitors have an effective area of 240 mm square. The flux monitors are parallel-plate ionization chambers with the gap of 5 mm. The output current from the flux monitor is digitized by the current-frequency converter having maximum frequency of 2 MHz. The beam position and profile are measured with a multi wire proportional counter (MWPC), which will be set just after the main and sub monitors. While the MWPC needs to have controlled gas flow, the flux monitor operates in air. The electronics of position monitor outputs the beam center with the repetition of 200 kHz. Further, additional functionality of 2D imaging is possible.

Mini ridge Filter and Range Shifter

The Bragg peak of the pristine beam is slightly broadened to produce a "mini peak" by using a mini ridge filter (RGF). The shape of bar ridge is designed to make Gaussian shaped mini peak of 3 mm width at 1-sigma. The RGF consists of 160 bar ridges made of aluminum, and has an effective area of 240 mm square. The distance between the RGF and the iso-center is set to be 1 m.

The range shifter (RSF) is used to precisely change the range slice-by-slice in the target. In order to reduce the beam size expansion by multiple scattering, the RSF is located close to the iso-center. The entrance and exit of RSF are 0.9 and 0.6 m upstream of the iso-center, respectively. This binary type RSF is consists of ten acrylic plates. Each plate has the thickness of 0.2 ~ 102.4 mm with an effective area of 240 mm square. By using the compressed-air cylinder, it takes around 300 ms to move/remove each plate.

Control System for 3D Scanning Delivery

A schematic drawing of the scanning control system is shown in Fig. 4. The scanning beam delivery is realized by specific controllers which consist of the high-speed part (order of 100 ns) and the low-speed part (order of few ms). The high-speed part consists of FPGA and memory modules on the VME crate. In order to avoid any problems with the CPUs during irradiation, the CPUs on the VME crates are only used to download/upload the data to the memory modules, and they are not used to control the beam delivery. Each memory module has a memory area for 22M spots. The low-speed part, including the system monitoring unit and the RSF controller, consists of the PLC and their I/O modules. This part controls and monitors the components having slow response, such as the RSF.

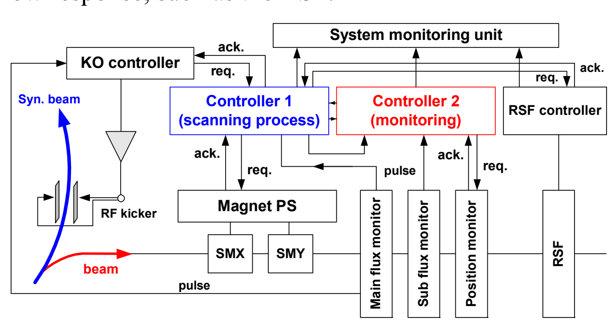

Figure 4: Schematic of scanning delivery control

The control system of the high-speed part has two VME crates controller 1 and 2. The main task of controller 1 is to perform the scanning irradiation process excluding the monitoring, and that of controller 2 is to monitor the scanning process. Controller 1 counts the digitized beam signals from the main flux monitor, and realizes the scanning irradiation sequence. On the other hand, controller 2 monitors the scanning process by using the beam position monitor and sub flux monitor. The KO controller1 is used to control the RF-knockout electrode in the synchrotron and to deliver the beam with required current level while keeping its uniform time structure.

PERFORMANCE TEST

Beam Monitors

Firstly, small recombination and small position dependence of main and sub flux monitors output were verified. On the other hand, two different features of beam position monitor was also verified: 1) calculation of beam center and 2) production of the 2D fluence map for each slice. Figure 5 shows the beam center outputs for scanned beam. The measured beam position as output of the monitor was in good agreement with the preset value of the beam position, and the standard deviation was less than 0.4 mm for each position. Figure 6 shows the typical result of 2D imaging compared with predicted one. This is very useful tool for quick verification of beam delivery.

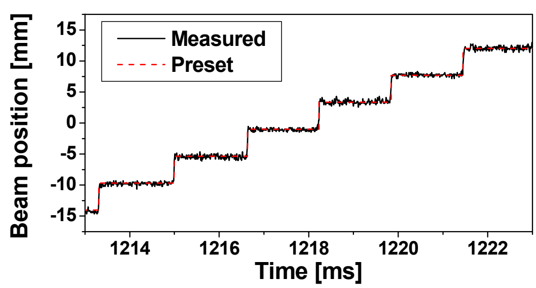

Figure 5: Typical output of beam position monitor.

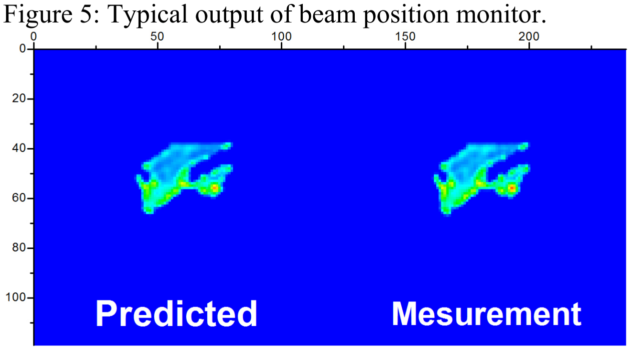

Figure 6: Typical result of 2D imaging using the position monitor.

2D and 3D Scanning Beam Delivery

A fluorescent screen with CCD camera [6] is very useful tool for 2D measurement in the scanning delivery verification. By applying calibration using the film measurement, it was possible to remove artifacts from 2D images caused by variations in the pixel-to-pixel sensitivity of the detector or screen and by distortions in the optical path between the screen and the detector. We employ this device for 1) calibration of the scanning magnet deflection, 2) observation of beam symmetric property and 3) check of lateral uniformity of delivered field. Figures 7 show typical results of 1) and 3).

For the verification of 3D delivery, the spherical shaped target of 60 mm diameter was planned to generate uniform physical dose field of 1 Gy. As shown in Fig. 8, the dose distributions measured by ionization chamber were in good agreement with the planned one at various penetration depths. In this target case, this system takes only 20 s to deliver the target with 8 rescans, cooperating with the planning software for fast scanning [7].

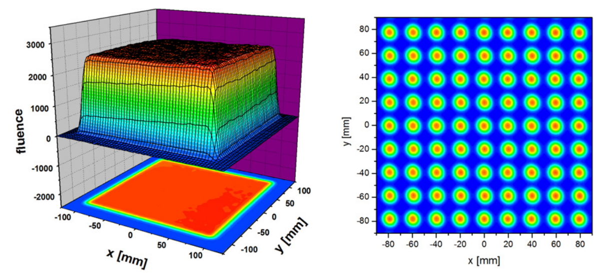

Figure 7: Measured images by the fluorescent screen system.

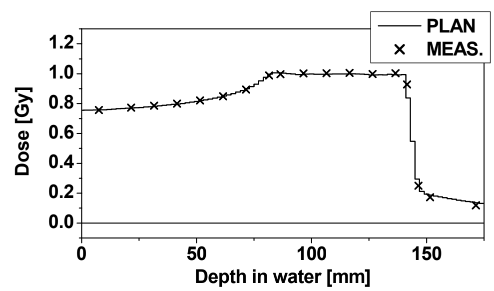

Figure 8: Comparison between measured and planned dose distribution.

SUMMARY

The performance test of the fast scanning system for the HIMAC new treatment facility were successfully carried out. As a result of this demonstration of fast scanning, rescanning with a gating scheme within an acceptable irradiation time, has taken a large step toward practical realization. Until the end of fiscal year of 2010, this scanning system will be installed and commissioned in the new facility.

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