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Development of NIRS pencil beam scanning system for carbon ion radiotherapy

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ABSTRACT

At Heavy Ion Medical Accelerator in Chiba (HIMAC) in National Institute of Radiological Sciences (NIRS), more than 9000 patients have been successfully treated by carbon ion beams since 1994. The successful results of treatments have led us to construct a new treatment facility equipped with a three-dimensional pencil beam scanning irradiation system, which is one of sophisticated techniques for cancer therapy with high energetic ion beam. This new facility comprises two treatment rooms having fixed beam lines and one treatment room having rotating gantry line. The challenge of this project is to realize treatment of a moving target by scanning irradiation. Thus, to realize this, the development of the fast scanning system is one of the most important issues in this project. After intense commissioning and quality assurance tests, the treatment with scanned ion beam was started in May 2011. After treatment of static target starts, we have developed related technologies. As a result, we can start treatment of moving target and treatment without range shifter plates since 2015. In this paper, the developments of the scanning irradiation system are described.

1. Overview of NIRS scanning system

To make optimal use of characteristics of carbon ion beams and to achieve accurate treatment, three-dimensional (3D) pencil beam scanning [1–3] is one of the sophisticated techniques. For implementation of this irradiation technique, at HIMAC [4], a new treatment facility [5] was constructed. The challenge of this project was 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. Here, moving target means mobile tumor, such as lung and liver, due to patient's respiration. Such respiratory motion is nearly sinusoidal and having amplitude of 10–20 mm and cycle of 3–5 s, typically. To treat such moving target by scanning irradiation is strongly required to obtain better dose conformation. Our approach [6–8] is a combination of the rescanning technique and the gated irradiation method. One of the most important features of our system is fast scanning to realize moving target irradiation with a relatively large number of rescans within an acceptable irradiation time.

Table 1 shows a basic specification of NIRS scanning system. Field size and maximum range are determined to cover most of the target that are treated by the existing passive irradiation system at the HIMAC. Under these conditions, the new system must be as fast as possible to treat the moving target with rescanning. Based on the conceptual design study [6], the system was designed so as to provide a modulated dose delivery with beam-scanning velocities of 100 and 50 mm/ms at the isocenter. These scanning velocities enable us to achieve the fastest irradiation time of around 40 ms for an example uniform 2D field (1 slice) having a 102×102 mm^2 size with spot spacing of 3 mm. To fulfill these requirements, we made strong efforts to develop (1) the fast scanning magnet and its power supply, (2) the high-speed control system, and (3) the beam monitoring.

Fig. 1 shows a layout of the scanning irradiation system for fixed beam line, which has a 9 m length to the isocenter. To achieve the fast magnetic scanning, the distances from the scanning magnets, SCMX and SCMY, to the isocenter (IC) are set to 8.4 and 7.6 m, respectively. The vacuum window is made of 0.1 mm-thick kapton and located 1.3 m upstream from the isocenter. The primary beam shutter (FST) and the neutron shutter (NST) are placed downstream of the scanning magnets. The main and sub flux monitors (DSN_M and DSN_S), position monitor (DSN_P), mini-ridge filter (RGF) and range shifter (RSF) are placed after the vacuum window. Although range shifter had been used to adjust beam range until the end of preparation of 200 beam energies, it is not used now.

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Table 1
Basic specification of NIRS scanning system.

Specification	Value
Dose rate	>2 Gy/min/Liter (>5 GyE/min/Liter)
Moving target	Possible with high-speed rescanning
Energy	430–50 MeV/u
Energy steps	>200 steps
Beam intensity	3×10^7–1×10^9 particles/s
Field size	>220 × 220 mm^2 scanning region > 240 × 240 mm^2
Maximum range	>300 mm
Lateral scan speed	Vx > 100 mm/ms, Vy > 50 mm/ms
Energy (depth) change time	<300 ms
Mini ridge filter	2 types, 1 and 3 mm at 1-sigma peak width
Minimum spot staying time	25 µs
Spot spacing	Typically 2 or 3 mm in both longitudinal and transverse directions
Beam size at isocenter (in air)	Typically 2 ~ 4 mm at 1-sigma (depends on energy)

2. Technologies in NIRS scanning system

Fig. 2 summarizes technologies used in NIRS scanning system, which are accelerator technology, beam scanning, beam monitoring, beam control, and QA and dosimetry. Details of these technologies are described below.

2.1. Accelerator technology

Two important developments are introduced in this section, 1) extended flattop with multiple-energy operation, and 2) beam current control. To enable the energy variation during the irradiation and to increase the duty factor in gated irradiation, the extended flattop with multiple-energy operation [6,9] is necessary. This operation makes it possible to deliver different beam energies in single synchrotron cycle. The time to change beam energy is suppressed within 0.3 s by means of this operation. Fig. 3 shows example of this operation, in which 11 steps of energy variation is performed. This 11 steps energy variation had been routinely used from 2012 to 2015, in combination with range shifter plates for depth scanning. From September 2015, we started the routine use of more than 200 energy steps [10]. Another important technology is beam current (intensity) control by using RF-knockout extraction [11]. Fig. 4 show system configuration of beam current control (upper) and example of current control (lower). Dynamic range of beam current control is around 30. Such modulation capability is required to realize the phase controlled rescanning [6–8], in which each slice is irradiated within single gate duration by adequately controlling the beam intensity.

2.2. Beam scanning and monitoring

The scanning magnets [12] are designed to achieve the beam-scanning velocities of 100 and 50 mm/ms even in the maximum rigidity of 6.62 Tm. 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 is employed. Cooperating with powerful powersupply, a fast scanning velocity faster than 100 mm/ms is realized. Even in fast scanning, the accuracy of scanned beam position is very important for the quality of the delivered dose distribution. For this purpose we developed feedback control with real time measurement of beam position. In addition, we use feed forward control with hysteresis correction. By combining these two techniques, deviation within 0.5 mm is achieved. This configuration is schematically shown in Fig. 5.

In this measurement of beam position, the beam position monitor (DSN_P in Fig. 1) is employed, which consists a multi wire proportional chamber (MWPC) having 120 anode wires for x and y planes, respectively. The output signals of the amplifiers of this MWPC are fed into the 12 bit analog-digital converters (ADCs), which operate with the frequency of 200 kHz to achieve fast beam monitoring. By using these digital data, this digital unit handles two different tasks: 1) calculation of beam center and 2) production of the 2D fluence map for each slice. These outputs are used for online display of the beam scanning process. Fig. 6 shows the typical view of position monitor console, which gives the information of scanning process.

2.3. Control system

The scanning beam delivery is realized by specific controllers which consist of the high-speed control part (order of a few hundred nanoseconds) and the low-speed control part (order of a few milliseconds). The high-speed part consists of field programmable gate arrays (FPGAs) and memory modules on the versa module europa (VME) crate. The important 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 process, i.e. controls the currents of the scanning magnets, the beam ON/OFF, the beam intensity (beam current level) and the accelerator settings in accordance with the beam steering file. Further, the setting values returned from these devices or controllers are stored in the memory modules on controller 1. On the other hand, controller 2 monitors the scanning process by using the beam position monitor and sub flux monitor. The beam position is compared with the predicted one just before each spot transition.

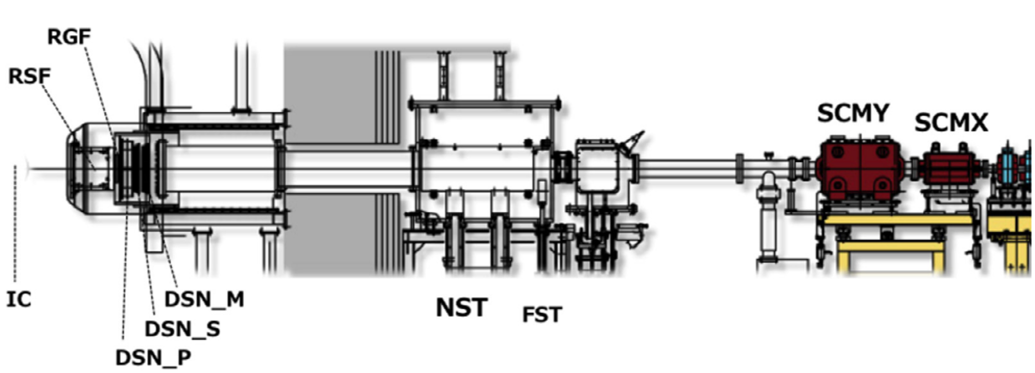

Fig. 1. Layout of the NIRS scanning system for fixed beam line.