RECENT PROGRESS ON HIMAC FOR CARBON THERAPY

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Abstract

An impressive advance of the carbon-ion therapy using the HIMAC has been supported by a high-reliability operation and a development of accelerator technologies. Based on the development of the accelerator-technology as well as the progress on the HIMAC treatment, we have proposed the new treatment-facility project for the further development of heavy-ion therapy. The study and R&D works for this project have seen successful progress, and the facility has been constructed since February 2009.

INTRODUCTION

Since the first clinical trial on three patients in June 1994 with 290 MeV/n carbon beam, the cancer treatment at HIMAC [1] has been successfully progressed and the total number of patients exceeded 4,500 as of February 2009. In some of the treatments with HIMAC, however, we have observed a change of the target-size and -shape during the entire treatment procedure. In order to keep the sophisticated conformations of dose distribution even in such cases, treatment planning should be carried out immediately before each fractional irradiation, which is called "adaptive cancer therapy". The broad-beam irradiation method [2], which has been routinely utilized at HIMAC, cannot realize the adaptive therapy, because this method requires bolus and patient collimators that take almost one week to manufacture. Therefore, we decided to utilize the 3D scanning with a pencil beam [3-5], because this method has brought about high treatment accuracy even in an irregular target shape without any bolus and patient collimators. However, this method has not yet been applied to treating a moving target with patient's respiration in practical use. Toward the adaptive cancer therapy, therefore, we have proposed the new treatment-facility project through improving the 3D scanning method and upgrading the HIMAC accelerator complex. In this report, we review the recent progress on HIMAC and the design of the new treatment facility.

PROGRESS ON ACCELERATOR

Improvement of Time Structure of Spill

We developed the RF-KO slow extraction method [6] for a respiration-gated irradiation system [7] using the wobbler method as one of the broad-beam methods, and the gated irradiation method has been routinely utilized for treating moving-tumours, since 1996. The RF-KO method has a huge ripple of kHz order in time structure of the extracted beam (spill) due to the coherency in its extraction mechanism. However, the huge spill ripple has never disturbed the dose distribution in the wobbler method, while it disturbs in the beam-scanning method, because the disturbance magnitude depends on the difference between the ripple and wobbler frequencies. Thus we developed the dual FM method and separated function methods [8] in order to significantly suppress the spill ripple. Further, we have also developed the method to suppress a fluctuation of Hz order in the time structure by optimizing AM function of the RF-KO system [9]. Typical time structure is shown in Fig. 1.

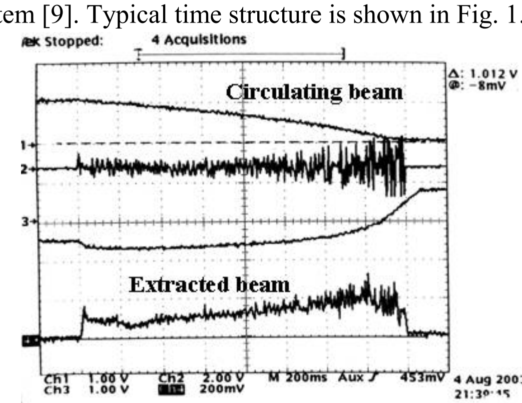

Figure 1: Typical time structure of an extracted beam.

Control of Beam Profile and Position

In order to deliver the beam with the desired profile and positions at a target through a beam-transport line, it has been essential to match the beam-optical parameters with those at an extraction channel of the ring. For the optical matching, thus, we developed an accurate prediction method of the optical parameters at the extraction channel through an outgoing-separatrix estimated by a rod-monitor measurement [10]. As a result of the experiment, it was verified that the predicted beam-optical parameters was in good agreement with the measured ones, as shown in Fig. 2.

We also investigated the beam-position stability. It was found that the beam position was changed according to a change of cooling-water temperature under a cold-start operation and a change of residual-fields of the synchrotron magnets after the high-energy and low-energy operations. Concerning the cold-start operation, it takes longer time for the water temperature to reach a saturated temperature. Concerning the residual-field change of the synchrotron magnets, we have developed a system to compensate the daily fluctuation of horizontal tune by changing the correction quadrupole field in the ring with monitoring the beam profile. As a result of a preliminary test, this system makes it possible to keep the beam position and intensity constant at the iso-center.

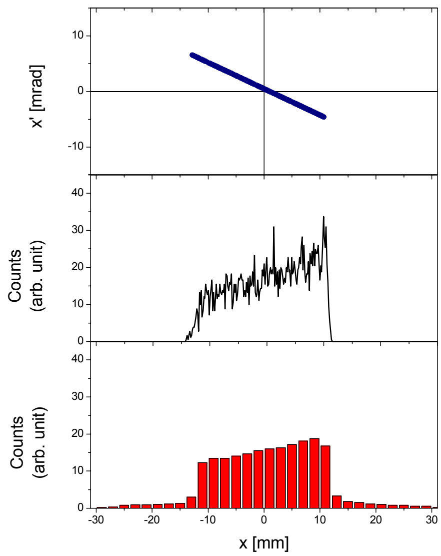

Figure 2: Comparison of the horizontal beam profiles obtained by simulation and profiles obtained by the experiment. From upper figure, the phase-space distribution estimated by the rod-monitor measurement, the predicted profile and the measured one.

Intensity Upgrade

In order to increase the delivered beam intensity, the optical-parameter matching in the vertical direction was carried out during a multi-turn injection into the synchrotron ring. As a result, the vertical emittance was decreased to 15 from 33 π·mm·mrad before matching. Increasing the beam intensity in the ring, we observed a large beam loss due to the space-charge effect. Since the vertical tune of 3.13, used in the routine operation, is close to the integer resonance through the incoherent tune-shift under high ion density after bunching, we changed it to 3.23. Even in this tune, however, the 3rd-order coupling resonance ($Qx + 2Qy = 10$) caused a large beam loss. We thus tested the resonance correction by using four sextupoles. After the correction, the beam lifetime was increased by more than 5 times under (Qx,Qy) = (3.74,3.23). An un-tuned RF-cavity, further, having a Co-based amorphous core, has been developed so as to make multi-harmonics operation possible for reducing the longitudinal space-charge effect [11]. By the multi-harmonics operation, the beam intensity was increased by 40%. As a result of studies mentioned above, more than 2×10^{10} carbon ions can be delivered to the iso-center with one operation cycle of the ring.

R&D STUDY FOR PCR METHOD

Toward the adaptive cancer therapy, as the first stage, we carried out a simulation study of the 3D scanning with gated irradiation for a moving target. Even using this method, however, we observed hot and cold spots in the dose distribution. Therefore, we have proposed the phase-controlled rescanning (PCR) method [12]. In the PCR method, the rescanning completes the irradiation on one slice during one gated period. Since the movement of the target is close to "zero" on average, thus, we can obtain the uniform dose distribution even under the irradiation on the moving target. The PCR method has required mainly two technologies:1) Intensity-modulation technique for a constant irradiation time on each slice having a different cross section and 2) Fast-scanning technique for completing several-times rescanning within a tolerable irradiation time.

Intensity Modulation

We have developed a spill control system [13] in order to deliver a beam with an intensity modulation, based on the improvement for suppressing the spill ripple with kHz order and the spill fluctuation with Hz order, mentioned at the section 2.1. The core part of this system requires the following functions: 1) calculation and output of AM signal according to request-signals from a irradiation system, 2) real-time processing with a time resolution less than 1ms, and 3) feed-forward and feedback controls to realize the extracted intensity as requested. This system allows us to control dynamically the beam intensity almost as required, as shown in Fig. 3.

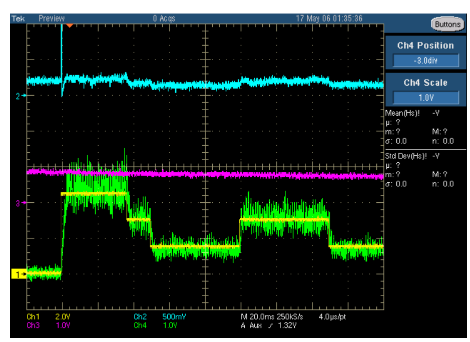

Figure 3: Time structure of extracted beam obtained by the spill control system. Spill time structure (green) can be modulated by request signal (yellow).

Fast Scanning

For the fast 3D-scanning, we have developed three key-technologies as follows:
1) New treatment planning for raster scanning
2) Extended flattop operation of the synchrotron
3) High-speed scanning magnet

New treatment planning

The raster-scanning has been chosen in order to save the irradiation time, instead of the spot scanning, because the raster-scanning does not require the beam-off period during the raster-position movement. In the raster scanning, on the other hand, it is inevitable to deliver an extra-dose on the position between the raster-points. It is noted that the extra-dose is proportional to the delivered intensity. Owing to the high reproducibility and uniformities in the time structure of the extracted beam through the spill control system, we can predict the extra-dose and incorporate its contribution to the treatment planning. Consequently we can increase the beam intensity and shorten the irradiation time. It was already verified by the simulation and experimental study [14].

Modified synchrotron operation

Owing to a high beam-utilization efficiency of around 100% in the scanning method and to the intensity upgrade to 2×10^{10} carbon-ions, we can complete the single-fractional irradiation of almost all treatment procedures in single-operation cycle of the synchrotron, This single-cycle operation, which can be realized by using a clock-stop technique in the flattop period, can increase the treatment efficiency especially for the gated irradiation. Thus we have proposed the extended flattop operation of the synchrotron. In this operation mode, the stability of the beam was tested, and it was verified that the position- and profile-stability were less than ±0.5 mm at the iso-center during 100 s of the extended flattop operation. This extended flattop operation can shorten the irradiation time by a factor of 2.

Applying the extended flattop operation, furthermore, we have developed a variable-energy operation with the single-cycle operation of synchrotron toward the range-shifter-less treatment. As the first stage, we have tried to extract beams with the energy chosen from eleven-step energy in one operation file by using the clock-stop technique as the same way with the extended flattop operation. After fine tuning for extraction, it was verified that the beams were successfully extracted with eleven-step energies. As the second stage, we will prepare 150-step energies in the operation file. When it will be completed, we will deliver the variable-energy beams for the scanning system.

High-speed scanning system

The scanning speed is designed to be 100 mm/ms and 50 mm/ms in the horizontal and vertical directions, respectively, which are faster by around one order than that in the conventional one. In order to increase the scanning speed, we designed the scanning magnet having slits in both the end of magnetic pole, according to a thermal analysis including an eddy-current loss and a hysteresis loss. The power supply of the scanning magnet was designed for the fast scanning, and this consists of two stage circuits; the first stage for voltage forcing by IGBT switching elements and the second stage for the flattop-current control by FET switching ones. As a result of the test, a temperature rise was measured to be around 30 degree at maximum, which is consistent with the thermal analysis.

RASTER-SCANNING EXPERIMENT

At the first stage, we have carried out a fast raster-scanning experiment by using the HIMAC spot-scanning test line [15]. The irradiation control system was modified so as to be capable of raster-scanning irradiation instead of spot-scanning. In the experiment, we adapted the measured dose response of the pencil beam with energy of 350 MeV/n, corresponding to a 22 cm range in water. The beam size at the entrance and the width of the Gaussian-shaped mini-SOBP were 3.5 and 4 mm at one standard deviation, respectively. The validity of the beam model and the optimization calculation had already been verified experimentally [16]. In the experiment, the extraction beam rate is highly stabilized during the extended flattop operation, owing to the spill control system, as shown in Fig. 4, and we have successfully carried out a 3D scanning experiment.

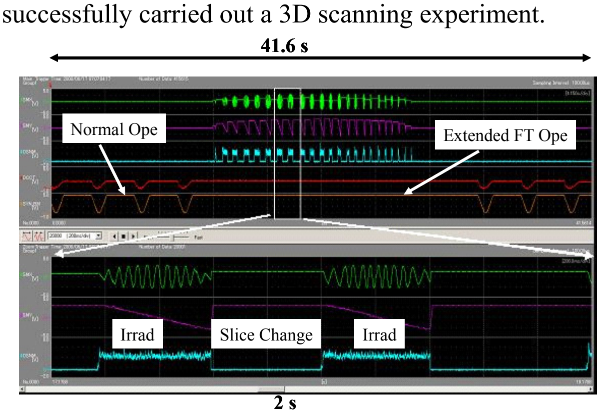

Figure 4: Extended flattop operation of the synchrotron. Upper: Current pattern of two scanning magnets (SMx and SMy), extracted-beam signal, RF-freq. pattern and Magnet pattern from upper trace, Lower: SMx, SMy, Extracted-beam signal from upper trace.

In the experiment, a spherical target of 4 cm in diameter was irradiated so as to produce a uniform physical dose field. The measured dose distributions were in good agreement with the designed ones at different penetration depths. Further, the dose distributions with/without the PCR method were two-dimensionally measured. As shown in Fig. 5, it was verified that the PCR method gave a uniform dose distribution even for the moving target. Owing to both the extra-dose prediction and the extended flattop operation, the irradiation time was shortened by around ten times compared with that of the conventional spot scanning.

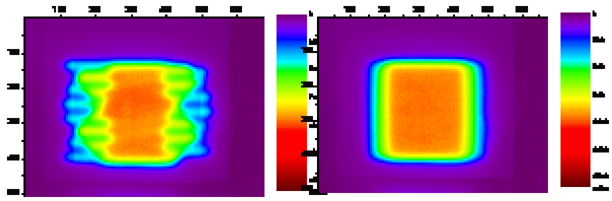

Figure 5: Dose distributions by the PCR method. Left: without PCR, Right: with PCR (8-times rescanning).

We designed and constructed a test irradiation port for the fast raster-scanning experiment in order to verify the design goal, which is the same configuration as the fixed beam-delivery system adapted to the new treatment facility as described in the section 5. Figure 6 shows the test port. In a preliminary test, we irradiated on a target with a spherical shape with 6 cm in diameter and obtained a uniform 3D dose distribution within 10 s even under 10 times rescanning.

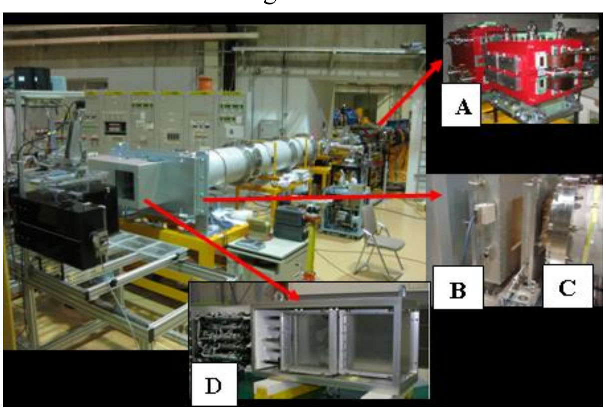

Figure 6: The test irradiation port of the fast 3D raster-scanning experiment. A: Scanning magnets, B:Position monitor, C: Dose Monitor, D: Range shifter.

DESIGN OF NEW FACILITY

Based on the development of the 3D fast raster-scanning, we have designed a fixed beam-delivery system, a rotating gantry system, a treatment flow including patient positioning and a facility planning for the new treatment facility.

Design Considerations

As a schematic view of the new treatment facility is shown in Figure 7, the facility is connected with the upper synchrotron of HIMAC. In the treatment hall, placed underground of the facility, three treatment rooms are prepared in order to treat more than the present number of patients at the existing HIMAC treatment. Two of the treatment rooms are equipped with both horizontal and vertical fixed beam-delivery systems, and the other one is equipped with a rotating gantry. Two treatment-simulation rooms are also equipped for obtaining CT-image for a treatment planning and for patient positioning as a rehearsal. Furthermore, there are six rooms devoted for patient preparation before irradiation.

In the new treatment facility, a ^{12}C beam is mainly used for the treatment procedures that have been carried out in the existing HIMAC facility. Different ion species will also be employed for future HIMAC therapy development. Thus, the maximum ion energy is designed to be 430 MeV/n in the fixed beam-delivery system in order to obtain the residual range of around 30 cm in a ^{12}C beam and more than that 22 cm in an ^{16}O beam. The maximum lateral-field and SOBP sizes are 25 cm × 25 cm and 15 cm, respectively, so as to cover almost all treatment needs with the HIMAC [17]. On the other hand, the rotating gantry system has a maximum energy of 400 MeV/n, a maximum lateral-field of 15 cm × 15 cm and a maximum SOBP size of 15 cm, in order to downsize the rotating-gantry size and weight.

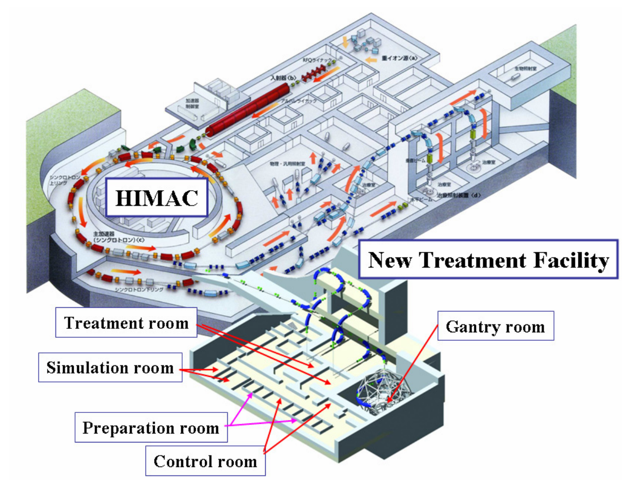

Figure 7: Schematic view of the new treatment facility.

Fixed Beam-Delivery System

The fixed beam-delivery system is designed to employ the PCR method, as shown in Fig. 8. The system consists of a pair of scanning magnets (SMx&SMy), a pair of profile monitors (PRN1&2), dose and position monitors (D&P), a ridge filter (RGF) and a range shifter (RSF). The total length of the system is around 9 m. The beam-scanning speed is designed to be 100 mm/ms and 50 mm/ms in the horizontal and vertical directions, respectively. Two dose monitors, which are parallel-plate ionization chambers with an effective area of 250 mm^2, are used for dose management. The beam position and size are monitored by multi-wire proportional counters. Considering the slice thickness, the Bragg peak is slightly spread out by a mini ridge filter. The range shifter is utilized to change the slice in the target. Thus, the range shifter should be as close as possible to the iso-center in order to avoid any change of the beam size by multiple scattering.

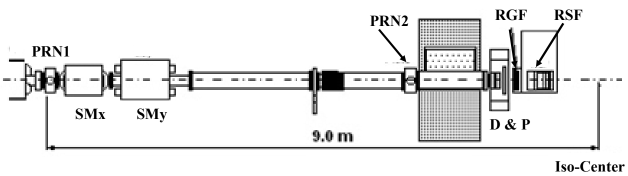

Figure 8: Fixed beam-delivery system. PRN1,2: Profile monitors, SMx and SMy: Scanning magnets, D&P: Dose and Profile monitors, RGF: Ridge filter, RSF: Range shifter.

Rotating Gantry

Owing to the good result on the development of the PCR method, a rotating gantry employs also the PCR method [18] in order to increase significantly treatment accuracy for a tumour located near to a critical organ through the multi-field optimization method [19]. Further, the rotating gantry can reduce considerably patient stress due to the face-downward attitude while the patient is positioned. It is important for the gantry design to avoid any change of the beam size depending on the rotation angle. Thus, we will adapt a compensation method of the asymmetric phase-space distribution [20].This method is based on multiple scattering by a thin foil placed at the position with the optimum beam-optical parameters in the BT line. Further, the final dipole magnet is divided into 30-degree and 60-degree magnets, and two scanners are placed between the two dipole magnets in order to extend the effective length from the scanners to the iso-center. The total weight of the rotating-gantry system is around 350 tons. A schematic view is shown in Fig. 8.

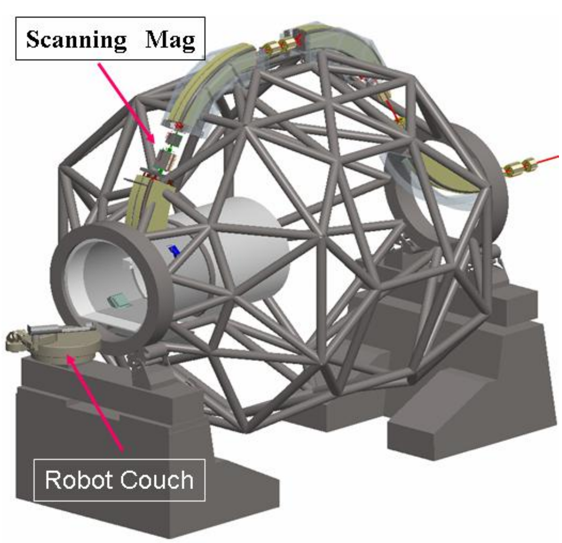

Figure 9: A schematic of view of a rotating gantry.

SUMMARY

During more than ten-years of clinical trials with HIMAC, both the beam-delivery and accelerator technologies have been significantly improved. Therefore we have proposed the new treatment facility project for further development of the HIMAC treatment. In this project, a patient positioning system, treatment planning system for the PCR method and Carbon-RT information system have been developed as well as that of the accelerator and beam delivery systems since April 2006. The construction of the facility building has been carried out since February 2009, and it will be completed at March 2010.

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