Raster Scanning Experiment with Extended Flattop of HIMAC Synchrotron

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A project to construct a new treatment facility as an extension of the existing HIMAC facility has been initiated for further development of carbon-ion therapy. In this paper, status of R&D works especially for the beam test has been reported.

I. INTRODUCTION

Heavy ion beams have attracted growing interest for cancer treatment due to their high dose localization and high biological effect at the Bragg peak. Thus, heavy ion cancer treatments have been successfully undertaken at various facilities around the world (Ref. 1-3). At HIMAC (Heavy Ion Medical Accelerator in Chiba), more than 3000 patients have been successfully treated by the use of carbon beams since 1994. For the purpose of further development of the therapy with HIMAC, new treatment-facility project was initiated in April 2006 (Ref. 4). This facility, which will be connected with the HIMAC accelerator, will consist of three treatment rooms: two rooms equipped with horizontal and vertical beam-delivery systems and one room with a rotating gantry.

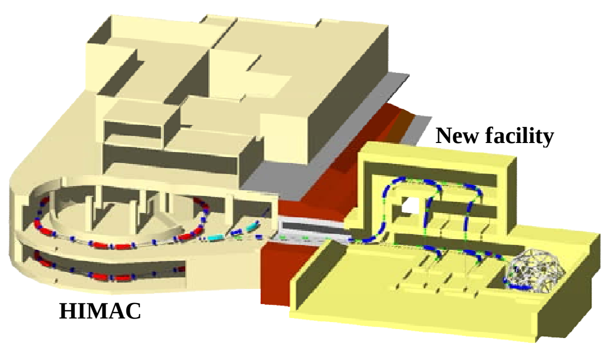

Fig. 1. Schematic view of HIMAC and its new treatment facility.

The greatest challenge of this project is to realize treatment of a moving target by scanning irradiation (Ref. 5). For this purpose, we decided to combine the rescanning technique (Ref. 6) and the respiration-gated irradiation method (Ref. 7). In order to reduce the irradiation time under the gated irradiation, in the new facility, we have decided to employ the variable extension of flattop, because single or double accelerations of HIMAC synchrotron can deliver a sufficient number of carbon ions for one fractional irradiation. For the verification of this scheme, we have carried out the experimental study of the raster scanning at a scanning test course (Ref. 8). The stability of beam position and size during the extended flattop was measured. Finally, it was verified that the dose uniformity of the irradiation field with raster scanning technique could be obtained cooperating with the variable flattop extension of the HIMAC synchrotron.

II. PRESENT STATUS OF DESIGN STUDY

II.A. Raster scanning irradiation system

To accomplish practical moving target irradiation, we decided to combine the rescanning technique and the gated irradiation method (Ref. 5). In 3D pencil beam scanning irradiation, the interplay effect between the scanning motion and the target motion brings about hot and/or cold spots in the target volume even in the gated irradiation, because the size of the distal and lateral dose profiles of the pencil beam is comparable to the residual motion range. Therefore, we decided to employ a combination of the rescanning technique and the gated irradiation method to avoid producing hot/cold spots.

To test our goal of producing a relatively large number of rescannings within an acceptable irradiation time, we carried out our design study in two steps: 1) conceptual design of a fast scanning system, and 2) simulation of moving target irradiation with rescanning and gating. The fast scanning strategy was studied with respect to the scanning method, the scanning magnets and their control. Based on the uniform time structure of beam from the synchrotron, we developed a novel optimization technique for fast scanning to cut the irradiation time, in which the exposure during transition of each spot is taken into account (Ref. 9). We performed simulation studies of irradiation of a moving target combined with rescanning and the gated irradiation method. We found that the phase-controlled rescanning (PCR) method (Ref. 5) gave a feasible solution in which the dynamic beam intensity control technique (Ref. 10) plays an important role to adequately control the phase correlation under a relatively small number of rescannings. In the PCR method, it is necessary to adjust the irradiation time for each depth slice to be within 1-2 seconds of the respiration gate width. Consequently, we obtained a feasible solution for moving target irradiation by our raster scanning method with rescanning and gating functions.

II.B. Modification of synchrotron control

In order to realize treatment of a moving target by scanning irradiation, one of key-technology is variable extension of the flattop. While the required number of particles per fraction is estimated to be low, due to high utilization of ions in the raster scanning irradiation, the HIMAC synchrotron can accelerate the carbon ions up to $2 \cdot 10^{10}$ in a single acceleration. Thus, modification of the synchrotron control system so it is capable of flexible flattop extension, called the "DC mode", is foreseen to decrease the dead time in respiration gated irradiation, as schematically shown in Fig. 2. Since single or double synchrotron accelerations can deliver a sufficient number of carbon ions for one fractional irradiation owing to this modification, the dead time of the synchrotron will be almost negligible. Such operations will much contribute to the respiration-gated irradiation with respect to the irradiation time.

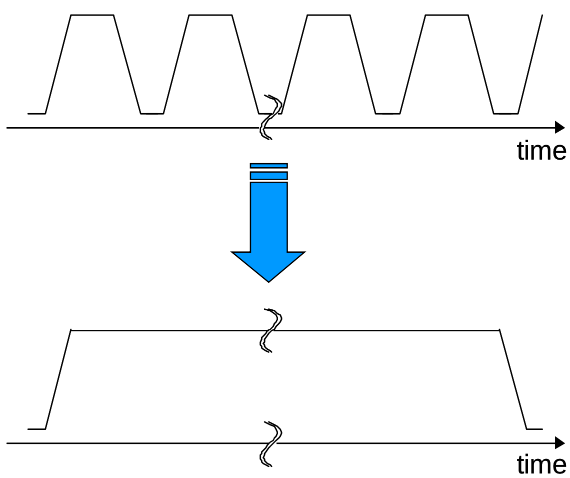

Fig. 2. Schematic of accelerator control modification to realize variable extension of flattop.

III. EXPERIMENTAL RESULT

III.A. Beam stability in extended flattop operation

Firstly, we have tested the stability of the beam. In this test, $2 \cdot 10^{10}$ carbon ions were accelerated up to 400 MeV/u and extracted with the constant rate of $2 \cdot 10^{8}$ particles/s during 100 s of the extended flattop. The extraction beam rate is highly stabilized owing to a dynamic intensity control system (Ref. 10) with RF-knockout slow-extraction (Ref. 11,12). This system controls the amplitude of the RF-knockout excitation using the approximated analytical approach and supported by the feed-forward and the feedback control; the latter employing both proportional and integral controls.

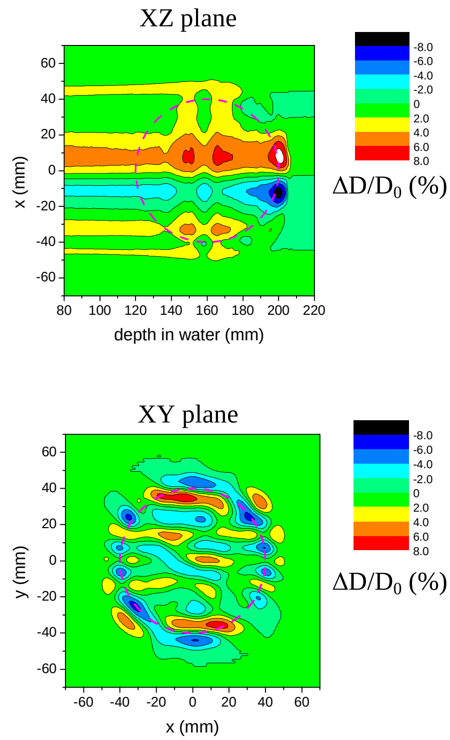

Fig. 3. Simulation result of percentage dose deviations in the XZ plane (Y=0) and in the XY plane (Z=center of SOBP).

In the 3D pencil beam scanning irradiation, on the other hand, the stability of the pencil beam is very important issue to assure the scanned field quality. Figure 3 shows one example of the simulation result to assess the beam stability effect. In this simulation, beam position was sinusoidally modulated with commercial frequency of 50Hz during the irradiation (spherical target of 80 mm diameter). Amplitude of the modulation was set to be ±2mm. It can be clearly seen that the dose homogeneity in the target volume deteriorates due to the worse position stability. Further, it was simulated that the long-term difference of the beam position and size during the irradiation bring more critical disturbance on the dose distribution. Therefore, the measurement of the beam profile during 100s extraction was also carried out to test the stability of both beam size and position. Figure 4 shows the measured beam profiles during 100s extraction. The measurement was carried out by using the wire grid profile monitor in the beam line where the beta functions are larger than that of the iso-center. By the analysis of this measurement result, it was calculated that both the position and size during the extended flattop are stabilized within ±0.5 mm at the iso-center position.

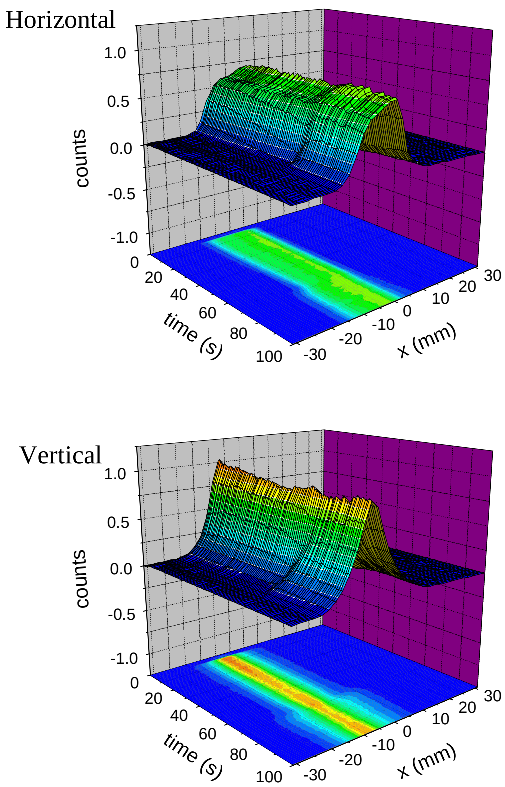

Fig. 4. Measured result of beam profile during 100s extraction.

III.B. Raster scanning experiment with extended flattop of HIMAC synchrotron

The raster scanning experiment with extended flattop of HIMAC synchrotron was carried out by using the HIMAC spot scanning test course (Ref. 6). The irradiation control system was slightly modified to be capable of the raster scanning irradiation instead of the spot scanning irradiation. Further, this control system can be used for the variable flattop experiment. In the present stage, we employed the measured dose response of the pencil beam with an energy of 350 MeV/u, which corresponded to a 220-mm range in water. The beam size at the entrance and the width of the Gaussian-shaped mini-peak were 3.5 and 4 mm at 1σ, respectively. The validity of the beam model and the optimization calculation had already been verified experimentally (Ref. 9).

Figure 5 shows the oscilloscope display in this experiment. Although there is a deviation of beam intensity in the first and second slices due to PI (proportional and integral) control of the dynamic intensity control system (Ref. 10), the beam intensity was almost kept during the irradiation. In the experiment, the spherical target of 40 mm diameter was irradiated to generate uniform physical dose field. The total irradiation time was decreased to 20 s due to extended flattop compared with the fixed cycle operation of 40 s. A cross monitor consisting of 128 small ionization chambers was employed to measure the dose distribution. This cross monitor operates with air at atmospheric pressure and room temperature. The 128 small ionization chambers are arranged in a way that 64 chambers are set in x direction and the other 64 chambers in y direction. It is also enclosed in a PMMA waterproof shell so that it can be inserted into the water tank and be moved in the beam line. The measured dose distribution was compared with the calculated one, as shown in Fig. 6. The measured dose distributions were in good agreement with the calculation result at different penetration depth. Furthermore, it should be noted that there was no difference of the field quality i.e. the homogeneity and absolute dose.

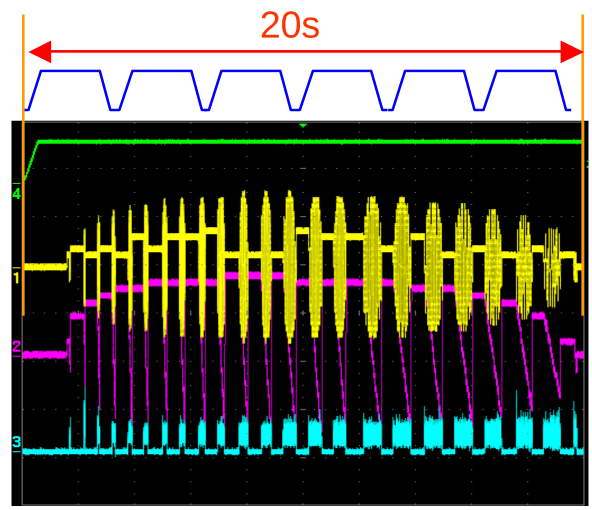

Fig. 5. Oscilloscope display in the raster experiment with extended flattop. From the top, the synchrotron bending magnets excitation current, the horizontal scanning magnet excitation current, the vertical scanning magnet excitation current and the beam spill signal. For comparison, the schematic of the fixed cycle operation (3.3s) routinely used at HIMAC is shown in the upper of the oscilloscope display.

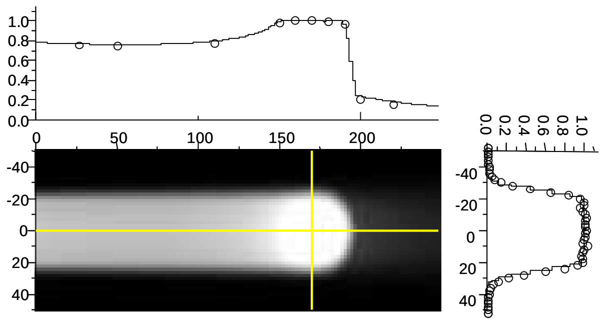

Fig. 6. Comparison between measured (open circle) and calculated (line) dose distribution.

IV. CONCLUSIONS

Design study of the raster scanning system and related R&D have been carried out at HIMAC. In the design study, owing to the uniform time structure of the beam from the synchrotron, a novel optimization technique was developed to reduce the irradiation time, in which the exposure during the transition of each raster point was taken into account. In the beam test based on this fast scanning strategy, the proof of principle was successfully verified cooperating with the highly stabilized beam under the variable extension of the flattop.

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