BEAM MONITORS OF NIRS FAST SCANNING SYSTEM FOR PARTICLE THERAPY

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Abstract

At National Institute of Radiological Sciences (NIRS), more than 6500 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 three-dimensional pencil beam scanning irradiation system. The commissioning of NIRS fast scanning system installed into the new facility was started in September 2010, and the treatment with scanned ion beam was started in May 2011. In the scanning delivery system, beam monitors are some of the most important components to safely deliver the dose to the patient. In this paper, the design and the commissioning of beam monitors in the delivery system are described.

INTRODUCTION

Since 1994, more than 6500 patients have been successfully treated with carbon-ion beams delivered from Heavy Ion Medical Accelerator in Chiba (HIMAC). 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 new treatment facility [4] was constructed. Figure 1 shows the treatment room of a new treatment facility. After intense commissioning and quality assurance tests, the treatment with scanned ion beam was started in May 2011.

Figure 1: Treatment room of the new treatment facility.

The beam delivery with beam scanning can be used to achieve the desired dose distribution by magnetically deflecting the beam across the target and by changing the beam penetration depth. Thus, scanning irradiation method requires sophisticated beam monitoring and control system to deliver well defined dose throughout the target volume safely with sufficient accuracy. In order to measure and control the dose of each spot, the main and the sub ionization chambers are placed separately as flux monitors. For monitoring of the scanned beam position, a beam position monitor, which is multi-wire proportional chamber, is installed just downstream from the flux monitors. This monitor can output not only the beam position but also the 2D fluence distribution using dynamic fast convolution algorithm.

In this paper, the design and the commissioning of these monitors in the delivery system are described.

NIRS FAST SCANNING SYSTEM

Layout of the scanning system [5] is shown in Fig. 2. It consists of the scanning magnets, main and sub flux monitors, position monitor, mini-ridge filter and range shifter. To achieve the fast beam scanning at the isocenter, the distances from scanning magnets to the isocenter are designed to be 8.4 and 7.6 m, respectively. The vacuum window is made of 0.1mm-thick kapton and located 1.3 m upstream from the isocenter. Beam monitors, mini-ridge filter and range shifter are installed downstream of the vacuum window. Since the required field size is 220×220 mm^2 for the transverse directions, the effective area of the monitors are designed to be 240×240 mm^2. Further, these monitors are designed to measure the beam having energies between 80 and 430 MeV/u, and having intensities between $1\cdot10^7$ and $1\cdot10^9$ particles per second (pps).

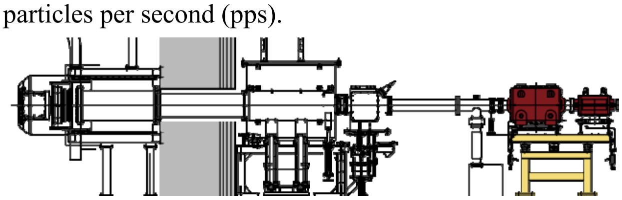

Figure 2: Delivery system of the new treatment facility. Beam monitors described in this paper are assembled in the region highlighted by red dot curve.

FLUX MONITORS

Configuration of Flux Monitor

The flux monitors, which are parallel-plate ionization chambers, are placed just after the exit window of the vacuum duct, and they are operated in air at atmospheric pressure. Each flux monitor consists of a signal foil

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(anode), two cathodes and two grounded shielding foils. For the cathodes, a wire mesh is employed to suppress the position dependence of the output signal. The wires (diameter: 50 μm) used in the mesh are made of gold-coated tungsten, and they are aligned with the spacing of 1 mm. The signal foil is made of 25 μm-thick polyimide, coated with Cu and Au. The gap between the anode and each cathode is 5 mm. With typical HV setting of –2500 V, the charge collection time is estimated to be 70 μs. Although such response of the chamber might cause an error in the dose delivery, the effect is considered to be tolerable, because the rising time of the beam at the beam ON timing is around 1 ms.

The output current from the flux monitor is digitized by the current-frequency converter. This converter module consists of the I/V amplifier (current to voltage amplifier) and VFC (voltage to frequency converter). Since cutoff frequency of the I/V amplifier is set to around 100kHz, the output response for 100 kHz input is –3 dB of the output response for DC input. The VFC can digitize the signal from the I/V amplifier with the conversion ratio of 0.4 MHz/V, while the maximum output frequency of the digitized pulses is 2 MHz. To cover the dynamic range of the expected beam intensity, this converter has three switchable ranges of 2MHz/100nA, 300nA and 1000nA. In the beam tests, the beam intensity of $1.5 \cdot 10^8$ pps is typically employed, providing digitized pulses of around 600 kHz under medium gain. Severe recombination of more than 1% has not been observed in the measured saturation curves of the flux monitor for different beam intensities.

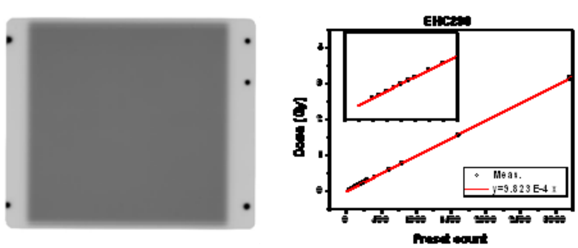

Figure 3: Typical result of flux monitor commissioning, left: position dependence measurement by film, right: output linearity measurement.

Commissioning of Flux Monitor

The position dependence of the main flux monitor and the scanning control was tested by using 2D uniform field irradiation. By applying the same count for regular grid spots, 2D uniform irradiation was carried out. The uniformity of the delivered field was measured by using the 2D ionization-chamber array (OCTAVIUS Detector 729 XDR, PTW Freiburg) and the film. Figure 3 shows results of 2D uniformity measurement by the film. We see a uniform field distribution, indicating the main flux monitor has rather small position dependence. In both measurements, the standard deviation of the measured dose was around 1%. From these results, we concluded the position dependent calibration of the flux monitor is not necessary. Output linearity of the flux monitor was also checked by changing applied count in 2D uniform field delivery. The delivered dose was measured by reference ionization chamber of PTW30013 having sensitive volume of 0.6 cc. As shown in Fig. 3, the deviation from the linear relationship was less than 1%. The measurement of the recombination was also carried out. Although the typical beam intensity was $1\text{-}2 \cdot 10^8$ particles/s, the severe recombination was not observed up to $6 \cdot 10^8$ particles/s.

BEAM POSITION MONITOR

Configuration of Beam Position Monitor

The beam position and profile are measured with a multi-wire proportional chamber (MWPC), which is installed just downstream from the main and sub flux monitors. With the anode wire spacing of 2 mm, this MWPC has 120 anode wires for x and y planes, respectively. Anode-cathode distance is designed to be 3 mm to avoid any gain drops due to the space charge effect. Diameters of the cathode and anode wires are 50 and 30 μm, respectively. Figure 4 shows a schematic drawing of this monitor system including its electronics, consisting of I/V amplifiers and a digital control unit. The I/V amplifiers, which have the amplification rate of $2 \cdot 10^6$ V/A, are directly connected to the monitor head. The output signals of the I/V amplifiers are fed into the 12 bit analog-digital converters (ADCs), which operate with the frequency of 200 kHz.

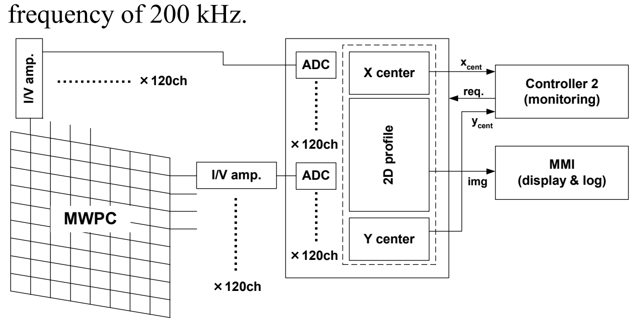

Figure 4: Schematic drawing of beam position monitor and its electronics.

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. The first task of the center calculation is carried out with a repetition rate of 200 kHz. When the beam position is required by controller 2, this unit provides the latest result of the beam center calculation. In controller 2, received data for the beam center are used for the interlock and irradiation log. Furthermore, this unit outputs an analog signal of the beam position which is fed into an oscilloscope to display the trajectory of the scanned beam. On the other hand, the second task of fluence map production for each iso-energy slice is carried out in the

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following steps. First, 11 channels around the beam center for each plane are selected. Second, by multiplying both profiles f(x) and g(y), the 2D image h(x,y) is calculated, while independence of each beam profile is assumed. This temporary image (11×11) is repeatedly summed into a full size image (120×120) during one slice irradiation. While the beam is OFF when changing the energy slice, the latest 2D fluence map is sent and displayed on the man-machine interface (MMI), while the digital unit prepares for the next slice, i.e. refreshing the image. Having repeated this procedure, the 2D fluence map for each iso-energy slice can be obtained.

Commissioning of Beam Position Monitor

Concerning the gain drop due to the space charge effect [6,7], the several types of gas mixtures are tested. Finally, we decided to employ a mixed gas of 70% He and 30% CF_4. The measured gain curve are shown in Fig. 5. Although the maximum gain was not so high, the intensity dependence was well suppressed compared with Ar based gases.

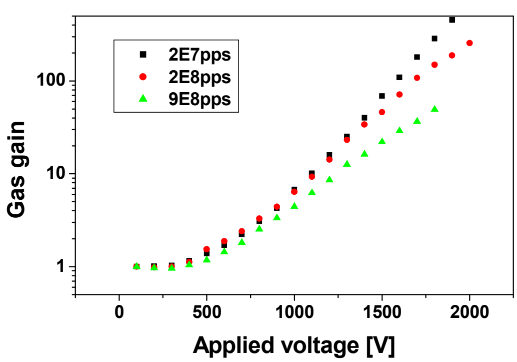

Figure 5: Measured gas gain with different beam intensities.

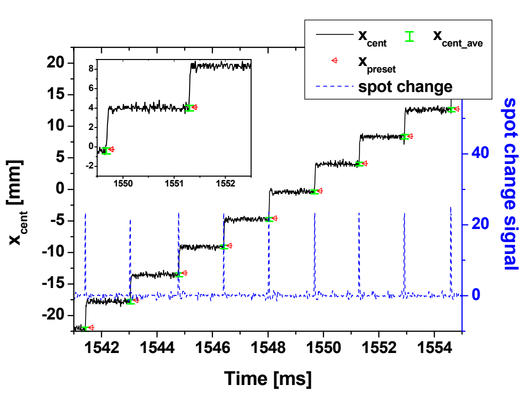

Figure 6: Beam center outputs (solid line) from the beam position monitor compared to the preset beam position (triangles). The average position between the spot transitions and the standard deviation are also plotted by bars. To clearly see the spot transition timing, the signal of transition is shown by the dashed line.

The verification of the beam position monitor output was carried out by comparing the film dosimetry. The differences measured position between the monitor output and the film were less than 0.5 mm. Further, the monitor performance was evaluated by using the measurement results. Figure 6 shows the beam center output during 2D uniform scanning irradiation. The average position of monitor output for each spot agreed well with the preset value within 0.5 mm. The standard deviation of the difference between the preset position and 200 kHz position output was less than 0.4 mm, corresponding to the accuracy of this monitor including its electronics. Consequently, the position monitor output can be used for position monitoring with the tolerance of 2 mm.

On the other hand, the position output is routinely used for online display of the beam scanning process. Figure 7 shows the typical view of position monitor console. Figure 8 shows typical oscilloscope display during the treatment. These displays give important information to medical staff during the irradiation process.

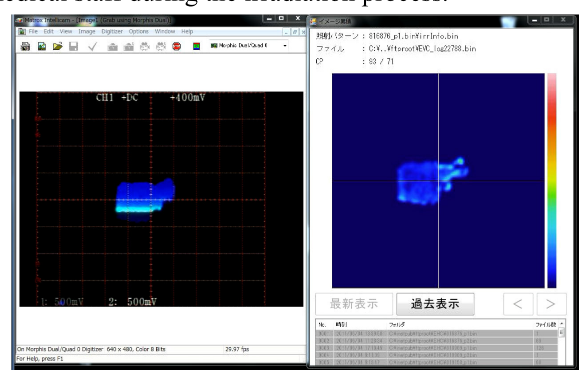

Figure 7: Online display of position monitor measurement, left: online display of beam position, right: measured fluence map for each iso-energy slice.

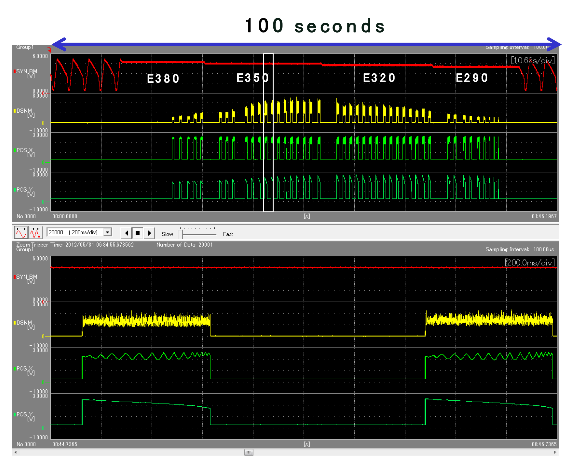

Figure 8: Typical oscilloscope display during treatment, lower trace shows the enlarged view of upper trace. Red line: synchrotron bending magnet pattern, yellow line: beam flux monitor output, green lines: position monitor outputs x and y.

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3D SCANNING BEAM DELIVERY

Verification of the scanning delivery system can be realized by checking the 2D delivery with intensity modulation. The checking irradiation pattern introduced by Flanz [8] was employed and measured by using the fluorescent screen with CCD camera system [9,10]. As shown in Fig. 9, we can see the 2D irradiation with the intensity modulation was successfully performed.

Overall check including the treatment planning system [11,12], the 3D dose conformation was tested by comparing measured and planned dose distributions. Typical result of comparison is shown in Fig. 10. Since the measured distribution was good agreement with the expected one, we can conclude that the beam control is correctly operating. The deviation was less than ±3%. Further, the reproducibility of the delivered dose within ±0.5% was also verified in these delivery tests.

SUMMARY

The scanning delivery system, including beam monitors, at the HIMAC new treatment facility were constructed and intensively commissioned. Consequently, the system are routinely used for the carbon-ion radiotherapy at NIRS-HIMAC.

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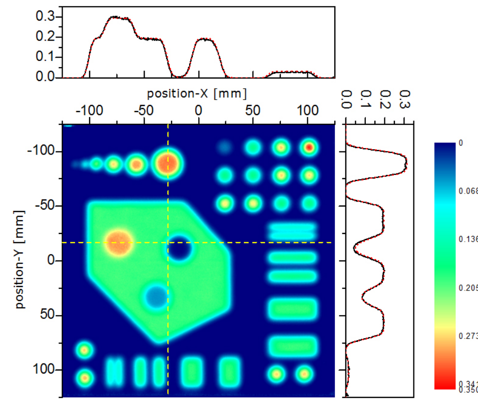

Figure 9: Measured distribution in 2D intensity modulation. Red dotted line shows the prediction.

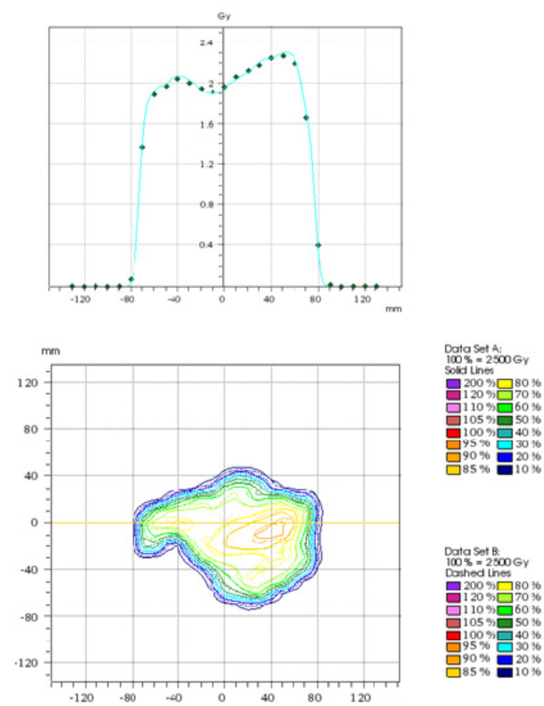

Figure 10: Comparison between measured and planned dose distribution. Upper trace: comparison on yellow line in lower trace, dot and line show measurement and plan, respectively. Lower trace: comparison of iso-dose line, solid contour shows measurement, while dashed contour show planned dose distribution.

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