BEAM CONTROL IN THE SPOT SCANNING IRRADIATION

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Abstract

Secondary beam course and its irradiation system have been constructed in HIMAC. In this system, positron emitter beam can be used to measure the irradiated volume with PET. As an irradiation method to use beam efficiently, the spot scanning irradiation was adopted. With this spot scanning system, irradiation test has been done with ^{11}C beam. In this paper, the current status of the beam control system will be presented.

1 INTRODUCTION

Since 1994, the heavy ion cancer therapy has been carried out at HIMAC (Heavy Ion Medical Accelerator in Chiba) in NIRS (Nation Institute of Radiological Sciences) [1]. With good clinical results, many kinds of tumors were treated and patient number was increased favorably [2]. Until now, accumulated total patient number became over one thousand in early 2001. In the irradiation, wobbler magnets and ridge filter are used to spread the beam laterally and longitudinally, respectively. This irradiation method is well established and reliable, and many patients were treated with nice clinical results. The important advantage of heavy ion therapy is its dose concentration on the tumor, and less dose on the normal tissue. To obtain correct ion range in the patient, we must depend on the calculation with X-ray CT data. Though this calculation is checked carefully, there will be still error in the calculation. One reason comes from the different process between the energy loss of the charged particle and the attenuation of X-ray, and the relation between these strengths depends on the material. In the heavy ion irradiation, margin of about 5mm will be added in its tumor boundary. If we use positron emitter, its shape of stopped activities can be measured directly with PET (Positron Emission Tomography). Though this provides unique tool to measure the range directly, the production rate is small. With the fragment separator in HIMAC [3], its value is smaller than 1%. With this beam intensity, efficiency of beam utilization in the irradiation system must be as high as possible. For this purpose, we have developed spot scanning irradiation system, where the knockout beam extraction [4] from the synchrotron is adopted. Concerning the 3d conformal irradiation system, several groups are discussing [5,6]. In their scenario, there is no beam on/off control during spot irradiation. But there is stringent requirement on the spill homogeneity in the slow beam extraction. In our system, the extraction is stopped during the period of transit time from one to next spot irradiation. During the period of beam off, we can check the previous spot in its dose value and spot position, which is important for quality assurance in the irradiation. This quick on/off became possible easily with RF knockout beam extraction, which is firstly realized for daily operation in HIMAC. In the beam control, speed of beam on and off must be fast to keep accurate dose control in each spot. In this paper we describe the irradiation system and some experimental results of beam control.

2 IRRADIATION SYSTEM

2.1 Devices

In the irradiation system, there is a pair of scanning magnets with which we can move spot position from one point to next quickly. The sweep speeds are 5 mm/ms and 2.5mm/ms with horizontal and vertical magnets, respectively. These speeds are required to keep the transit time shorter than the current expected irradiation time of few minutes. The spot depth can be controlled with range shifter that is placed just in front of the patient position. The thickness can be adjusted by the combination of ten acrylic plates. With this combination the thickness can be adjusted from 0mm to 159.79mm with minimum thickness of 0.29mm. Required time is 480ms to change the thickness with different combination of the plates. As this period is longer than the one of scanning with magnets, we change the range shifter thickness after the irradiation of all spots in one layer. To measure the dose of each spot, we have used two parallel plate ionization chambers as main and sub dose monitors. One is for control and another one is for check. There are profile monitors of horizontal and vertical directions, and the beam position scanned with magnets is checked. There is multi-leaf collimator to cut the distribution tail, which is installed downstream of the beam monitors. In Fig. 1, arrange of these devices are shown together with the other devices of collimator and PSD (Position Sensitive Detector).

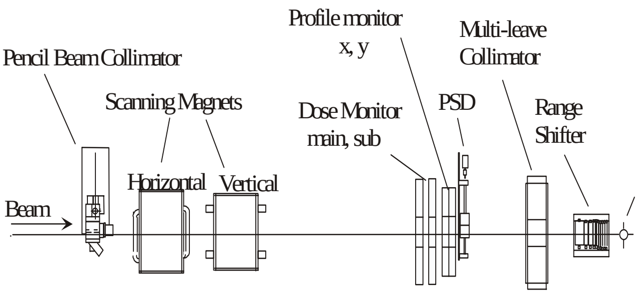

Figure 1. Irradiation system in the secondary beam course.

2.2 Control system

In the control system, there are two groups. One group is for controls of each spot that requires fast response, and another group is for slow control. Former devices are controlled with pattern data in the four VME modules, and the latter group is controlled with PLC. In the VME system, four modules are connected to the irradiation devices as follows:

1. VME1 – current data of scanning magnets(H/V), main dose monitor, multi-leaf collimator, range shifter
2. VME2 – sub dose monitor.
3. VME3 – horizontal position monitor.
4. VME4 – vertical position monitor.

With this arrange of VME modules, loads in each CPU in VME are distributed. Separate arranges of main and sub dose monitor is come from security consideration though its load is not heavy. There is a timing controller to obtain fast response with following signals.

a) Triggers to VME.
b) Interlock signals from all devices.
c) Flat top gate from synchrotron, generation of beam gate signal for each spot irradiation.

Timing sequence of control from one spot to next spot irradiation is shown in Figure 2.

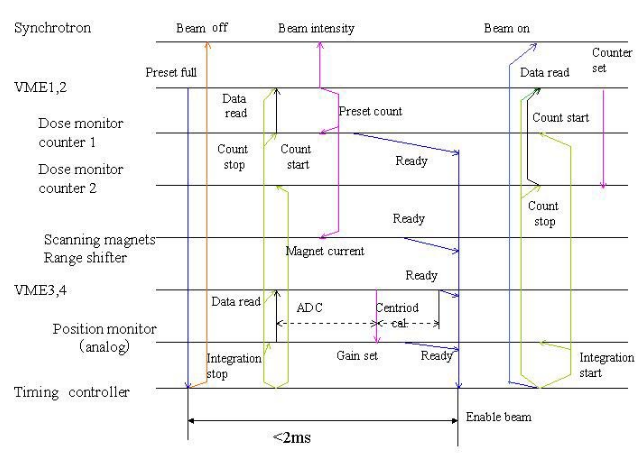

Figure 2. Control sequence between the spot irradiations.

3 EXTRACTION SYSTEM

In the beam extraction, we have used RF knockout method where the transverse rf field excites horizontal betatron oscillation. With this extraction device, we have quick control of beam on and off, which is required in this spot scanning irradiation. We have also merit with a fixed separatrix in the extraction process, where extracted beam axis will not move during whole period of extraction. The beam strength can be controlled with the amplitude of knockout rf field. To avoid spike shape of beam extraction, we will start with small rf amplitude at the beginning of the beam gate, and the amplitude was gradually increased. In Figures 3 and 4, beam spills are shown with this extraction, where the spill monitor has response up to 10 kHz.

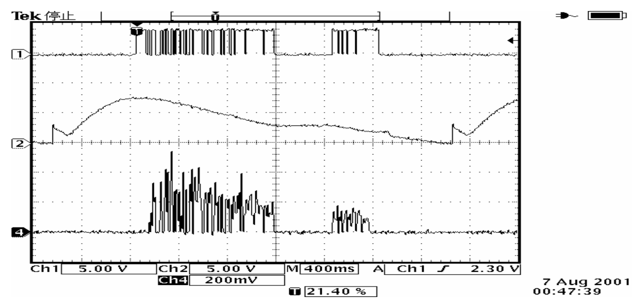

Figure 3. Upper trace is beam gate, middle one is beam intensity in the ring and lower one is extracted beam signal. One time division (horizontal axis) is 400ms.

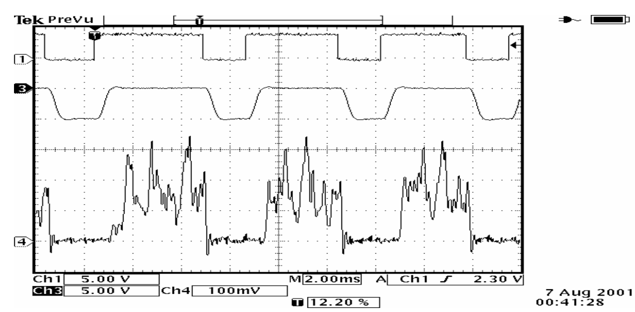

Figure 4. Beam spill signal in the successive small spots. One division (horizontal axis) is 2ms. Upper trace is beam gate, and middle trace is current of QDS magnet.

4 BEAM TEST OF THE SPOT SCANNING IRRADIATION

In the beam test of the spot scanning, simple case of irradiation volume was used. The irradiated volume of SOBP (Spread Out Black Peak) was 35×35×43mm^3 in the acrylic block, and the injected physical dose was 1Gy at the center of this volume. In the irradiation, 4050 spot points were used to form the required dose distribution in the above volume. The strength of each spot must be calculated from the data of lateral and depth dose distribution of the spot beam. The calculated results are shown in Figure 5 in the depth direction [7]. In the horizontal and vertical direction, spacing of each spot was 3mm to obtain smooth dose distribution.

At first, we measured the irradiation time varying the strength of rf knockout field with same ramp shape of the amplitude. As shown in Figure 6, we obtain shorter irradiation time with higher rf field. In the higher value, variation of irradiation time became small. This indicates that the accelerated beam can be extracted well, and we can't obtain the extracted beam further with higher voltage.

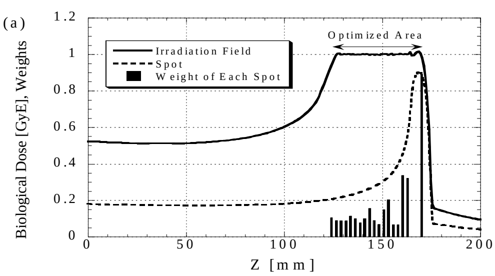

Figure 5. Depth distribution of biological dose. Dashed line shows the distribution of spot beam. Solid curve is superimposed data of each spot with weight of solid bar.

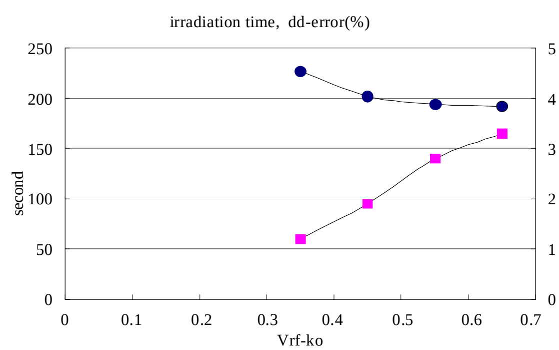

Figure 6. Irradiation time (upper data) vs. rf knockout field (relative). Lower data are error ratios (% in right axis) of extra dose due to cut off time of the beam extraction. Irradiated dose was 1 Gy (physical dose).

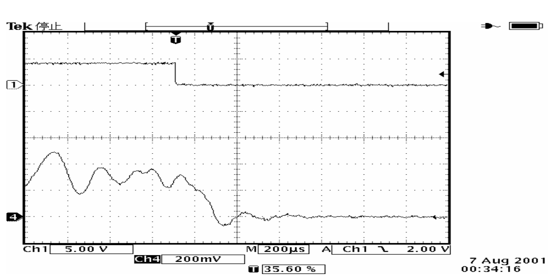

Figure 7. Beam gate (upper signal) and the extracted beam signal (lower one). One time division (horizontal axis) is 200µs.

Accurate control of each spot is required to obtain desired dose distribution in its shape and absolute value. For this requirement, cut off speed at the end of each spot should be fast. In the extraction system, turn-off of the rf knock-out power and the tune shift from resonance condition with small quadrupole magnet (QDS) in the ring are used to stop the beam extraction. With this system, beam extraction can be stopped within 200µs as shown in Figure 7. If we don't use the QDS, cut-off time become longer.

5 ESTIMATION OF ERROR

To estimate the effect of the above control speed for the dose distribution, calculated dose distribution (D(x,y,z)) and the surplus from that value (ΔD(x,y,z)) was estimated at the point (x,y,z). In the calculation, dose contributions from all spot beam are sum-up at the point (x,y,z) as follows:

$$D(x,y,z) = \Sigma_{ijk}\, W_{ijk}\, d(x-x_i,y-y_j,z-z_k)$$

$$\Delta D(x,y,z) = \Sigma_{ijk}\, \Delta W_{ijk}\, d(x-x_i,y-y_j,z-z_k)$$

Where d(x,y,z) is physical dose distribution of the spot beam, W_{ijk} is calculated weight of each spot, ΔW_{ijk} is measured difference from preset value, and (x_i,y_j,z_k) is coordinate of the each spot. This surplus will be large at the point where the dose consists from many small spots. So the excessive ratio (ΔD(x,y,z)/D(x,y,z)) will be large at the front end of the SOBP. In the beam test, the irradiated dose was 1 Gy (physical dose) and the beam intensity was about 7×10^6pps. The obtained results are shown in Figure 6 as a function of rf knockout voltage.

6 SUMMARY

In the spot scanning system, beam on/off control for each spot was adopted. Due to fast beam control with rf knockout extraction, the beam can be stopped within 200µs. Estimated dose error can be kept smaller than 2% with lower rf voltage, and the irradiation time was about 200 second with 1Gy (^{11}C beam) on the volume of $35\times35\times43$mm^3.

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