DESIGN OF COMPACT IRRADIATION PORT FOR CARBON RADIOTHERAPY FACILITY

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Abstract

A compact irradiation port for wide spread use of carbon radiotherapy is designed. The energy of carbon ions is planed to range from 140 to 400 MeV/n. The facility needs both of horizontal and vertical irradiation ports for an efficient treatment. The port length will be reduced to 5.5 m which equal to half length of HIMAC. The broad beam method will be used to produce a irradiation field up to 220 mm in diameter and 250 mm in depth. We propose an amplitude-modulation wobbler method, so called spiral wobbler method, to produce the large irradiation field using a small radius beam. The system has an advantage that the residual range at a patient position is longer than that produced by a conventional wobbler-scatterer method. In this paper, design for the compact irradiation port, especially for the spiral wobbler system, is reported.

INTRODUCTION

In the Heavy Ion Medical Accelerator in Chiba (HIMAC) [1] at the National Institute of Radiological Sciences (NIRS), clinical trials were started using carbon-ion beams of 290, 350, and 400 MeV/u in 1994. Around 1800 patients were already treated with the HIMAC facility and good results have been reported [2]. Therefore it is required to popularize the carbon radiotherapy. For the popularization, it is required to reduce a construction cost of a clinical facility. Now, therefore, we start to study a compact facility.

An irradiation port controls the beam in order to irradiate to a whole volume of a target tumor. A irradiation method is roughly classified into a broad-beam method, such as a wobbler-scatterer method [3] and a double-scatterer method [4], and a scanning method [5]. Figure 1 shows the concept of the wobbler-scatterer method. The accelerated beam is spread into Gaussian distribution by the scatterer. Then, the pair of the wobbler magnets scans the beam circularly. At the result, an uniform field is produced for lateral direction, and it is formed into the target shape by a collimator. For longitudinal direction, a spread-out Bragg peak (SOBP) is produced by a ridge filter and shaped for distal part of the field by a bolus. On the other hand, the scanning method scans the target volume with a narrow beam, three-dimensionally. All medical institutions in Japan use a broad-beam method, because this method can easily and accurately irradiate a target moving

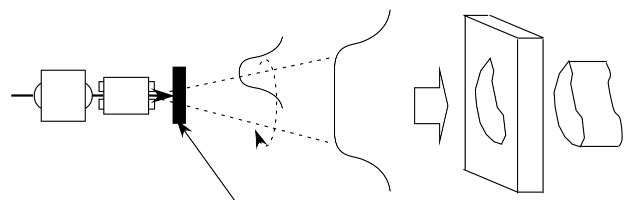

Figure 1: Schematic drawing of the wobbler-scatterer method. The wobbler magnets and the scatterer produce a uniform field and the collimator forms the field into a target shape for lateral direction.

along with a patient respiration (respiration-gated irradiation) [6]. Since the beam is mainly spread in the scatterer for the broad-beam method, the energy loss in the scatterer shortens the residual range at a patient position (isocenter). The beam radius at the isocenter should be more than the irradiation-field radius. As mentioned above, when the distance between the scatterer and the isocenter becomes short, the scatterer should be more thick to produce the field with the same radius. Consequently, the energy loss is to be increased and it shortens the residual range. Therefore, we develop a method to produce a large irradiation fields using a beam with a small radius. The scanning method can produce the uniform irradiation field in fixed target, while it is difficult to make a uniform field with respiration-gated irradiation. A multi-wobbler method with several different radii [3] can similarly produce a uniform field. It complicates dose control, however, because the dose for each wobbler radius must be managed precisely.

Therefore, we have propose an amplitude-modulation wobbler-scatterer method, so called spiral wobbler method [7] to produce a large irradiation field using a beam with small radius. The wobbler radius is modulated to produce the uniform field, resulting in the spiral beam trajectory. The proposed method has an advantage that the residual range at the isocenter is longer than that obtained by the conventional wobbler-scatterer method. Additionally, continuous modulation of the wobbler radius only requires control of the total dose. In this paper, design for the compact irradiation port, especially for the spiral wobbler system, is reported.

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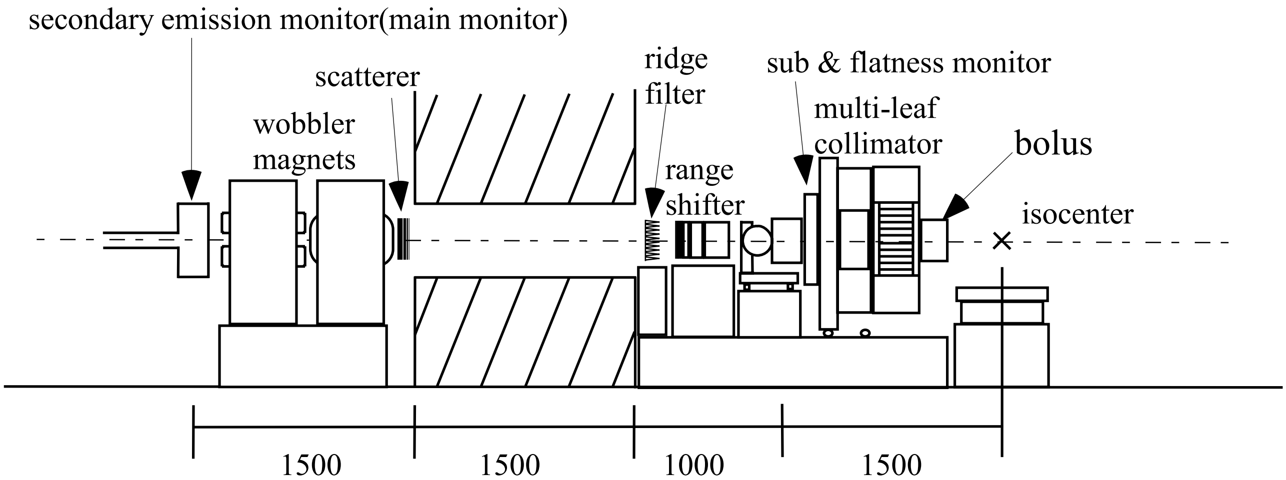

Figure 2: Schematic drawing of the compact irradiation port.

IRRADIATION PORT

Figure 2 shows the schematic drawing of the compact irradiation port. The port length is reduced to 5.5 m which equal to half length of HIMAC port. It consists of the wobbler system, beam-forming system and monitor system. The energy of carbon-ions is planed to range from 140 to 400 MeV/n, because a residual range needs 275 mm in water at least. The irradiation field is up to 220 mm in diameter and 250 mm in WEL (water equivalent length) in depth.

Spiral Wobbler Method

As mentioned above, the thickness of the scatterer should be increased in order to spread the beam radius further. On the other hand, the increasing of the scatterer shortens the residual range. Therefore, the beam radius is determined in order to maintain the residual range of 250 mm in WEL. Under the distance between the scatterer and isocenter of 4 m, the beam radius should be less than 30 mm (1σ) for the beam energy of 400 MeV/n. In the calculation, the multiple coulomb scattering in the scatterer and in the air between the scatterer and isocenter was considered.

The amplitude of the wobbler radius is modulated so as to uniform surface density of the beam fluence. As the result, the amplitude should be relative to the square root of the irradiation time. the amplitude (F) of horizontal and vertical wobbler-radius, which are a function of time (t), are written as

$$F = A\sqrt{(t-nT)/2T}\sin(\omega t+\alpha) : \quad nT \le t < (n+1/2)T, \tag{1}$$

and,

$$F = A\sqrt{((1+n)T-t)/2T}\sin(\omega t+\alpha) : \quad (n+1/2)T \le t < (n+1)T, \tag{2}$$

where A is the maximum wobbler radius, T the period of wobbler radius motion, ω the angular frequency of the wobbler cycle motion, and n an integer. The amplitude frequency of the wobbler radius and the angular frequency are planed to 23 and 59 Hz, respectively. The phase shift (α) between the horizontal and vertical wobbler is to be $\pi/2$. The first term of Eq. (1) and (2) represents the wobbler radius motion and the second term represents the wobbler cycle motion. The maximum wobbler radius (A) depends on the irradiation-field radius and the beam size.

It seems that the spiral wobbler method takes a longer time to produce a uniform irradiation field than the conventional wobbler-scatterer method because of a smaller beam radius. It is difficult to produce the uniform field when short-time irradiation are repeated randomly like the respiration-gated irradiation. In HIMAC, the typical gate time is 1 s for respiration-gated irradiation. Thus, the spiral wobbler system should realize uniform irradiation field within 1 s. We simulated the uniformity of the irradiation field of 22 cm in diameter as a function of the irradiation time. Typical result is shown in Figure 3. The amplitude frequency of 23 Hz, the angular frequency of 59 Hz, and the beam radius of 25 mm (1σ) are assumed. The time structure of the beam intensity affects the uniformity of the irradiation field. In HIMAC, since the beam is extracted from a synchrotron by means of the RF-knockout slow-extraction method, the beam intensity depends on the slow component of the whole time of the beam spill and the fast component [8]. Thus, the slow component was approximated by second polynomial functions in this simulation. The fast-component amplitude was approximated by a random number of $\pm$ 25% for 1 ms. The uniformity at the isocenter was calculated by integrating the beam fluence irradiated for each 5×5 mm^2 pixel. The beam profile spread by the scatterer was assumed to have a Gaussian shape.

Figure. 4 shows the uniformity of a 220 mmϕ field as a function of the irradiation time. The uniformity is defined by the ratio of minimum to maximum fluence in the

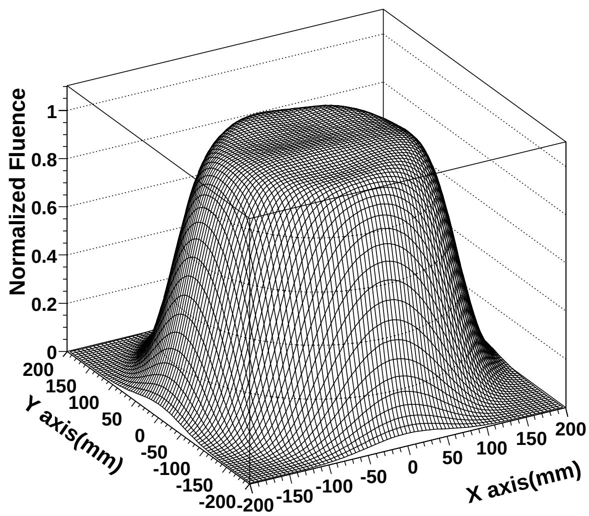

Figure 3: Typical results of the uniformity of the irradiation field. The field size is 220 mm in diameter and irradiation time is 1 s.

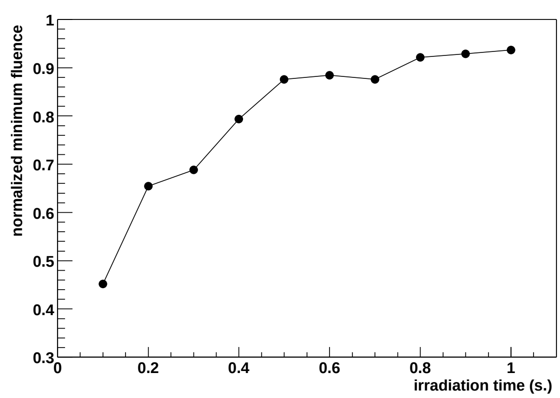

Figure 4: Uniformity of a 220 mmϕ field as a function of the irradiation time produced by the spiral wobbler method. The fluence is normalized by the maximum fluence in the field.

irradiation field. The uniformity is around $\pm$ 3 % under irradiation time of 1 s. The spiral wobbler method, therefore, can be adapted to the respiration-gated irradiation.

Beam-forming System

The beam-forming system consist of a bar ridge filter, range shifter, collimator, and bolus. The SOBP is formed by inserting ridge filters in the beam line. The ridge filter is fixed during irradiation. In order to smear out the shades of the bar ridge at the isocenter, the spacing of each bar ridge is less than 2.5 mm. The thickness of the SOBP is changeable from 4 to 15 cm in WEL by 1 cm in WEL step. The ridge filter is designed so that the survival fraction of human salivary gland tumor cells (HSG cells) should be uniform in the SOBP. Downstream of the ridge filter, a range shifter is placed to adjust the range in patients. The range can be adjusted in step of 0.5 mm by selecting various thicknesses of polymethyl metacrylate (PMMA) plates of the range shifter. A multi-leaf collimator is used for defining the lateral irradiation field for each patient. The leaf width of less than 3 mm is planed in order to omit a patient collimator. A bolus can be mounted on the housing of the multi-leaf collimator for shaping the distal part of the irradiation field.

Additionally a layer-stacking irradiation [9] is planed to produce the SOBP. Instead of the bar ridge filter, a single filter is used to spread the Bragg peak to the size of several millimeters in water. The resultant small SOBP is longitudinally scanned over the target volume in a stepwise manner. The method can avoid undesirable dosage to the normal tissue in front of the target when using the fixed SOBP produced by the bar ridge filter.

Monitor System

Dose-monitor system consists of two independent monitors: a secondary emission monitor (SEM) and a parallel-plate ionization chamber (PPIC). The SEM is used as a main dose monitor. The monitor is placed upstream of the wobbler magnet to measure the total dosage. The PPIC is used for a sub dose monitor. The chamber is placed upstream of the multi-leaf collimator. A multi-segmented ionization chamber is placed upstream of the sub monitor for checking the uniformity of the dose and the field size.

SUMMARY

We designed the compact irradiation port for carbon radiotherapy facility. The port length can be reduced to 5.5 m while keeping the maximum field size of 220 mm in diameter and 250 mm in depth. The spiral wobbler method contributes to reduce the port length. The method can be also adapted essentially to the respiration-gated irradiation.

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