TITLE OF THE INVENTION

PARTICLE BEAM IRRADIATION SYSTEM AND CHARGED PARTICLE BEAM CORRECTION METHOD

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001]

The present invention relates to a particle beam irradiation system and a charged particle beam correction method. The invention particularly relates to a particle beam irradiation system and a charged particle beam correction method suitable for adaptation to a particle therapy system for treating cancer by irradiating the target volume (tumor volume) with a charged particle beam (ion beam) of protons, heavy ions or the like.

2. Description of the Related Art

[0002]

Particle therapy, treating cancer by irradiating the tumor volume of the patient with an ion beam (protons, heavy ions, etc.), is widely known as radiotherapy for cancer. Methods selectable for the ion beam irradiation include the uniform scanning irradiation method such as the techniques disclosed in Japanese Patent No. 2596292 (hereinafter referred to as "Patent Literature 1"), JP-2009-28500-A (hereinafter referred to as "Patent Literature 2"), Japanese Patent No. 4158931 (hereinafter referred to as "Patent Literature 3"), Medical Physics, Volume 36, Number 8 (August 2009), Pages 3560 - 3567 (hereinafter referred to as "Non-

patent Literature 1"), and Review of Scientific Instruments, Volume 64, Number 8 (August 1993), Pages 2074 - 2093 (hereinafter referred to as "Non-patent Literature 2").

SUMMARY OF THE INVENTION

[0005]

To maintain the uniformity of the irradiation dose in the uniform scanning irradiation method, it is necessary to prevent the beam from being exhausted in the middle of one-unit irradiation (a unit of irradiation) of a prescribed area. On the other hand, the electric charge quantity of the ion beam accumulated in the synchrotron is not constant and varies in response to the electric current fluctuation of the ion beam supplied from the preaccelerator.

[0006]

When the accumulated electric charge quantity (cumulative electric charge quantity) is smaller than the electric charge quantity necessary for the one-unit irradiation, extracting (emitting) the beam from the synchrotron for the irradiation without any modification leads to exhaustion of the beam in the middle of the irradiation and deterioration in the uniformity of the irradiation dose. Conversely, not using the small amount of accumulated beam (insufficient for the one-unit irradiation) for the irradiation is disadvantageous in terms of beam utilization efficiency.

[0007]

It is therefore the primary object of the present invention to provide a particle beam irradiation system and a charged particle beam correction method capable of enhancing the beam utilization efficiency without deteriorating the irradiation dose uniformity.

[0008]

In accordance with an aspect of the present invention, there is provided a particle beam irradiation system comprising a synchrotron in which an ion beam is accelerated and from which the ion beam is then extracted and an irradiation device for irradiating a target volume with the ion beam extracted from the synchrotron. The irradiation device performs one-unit irradiation multiple times. The particle beam irradiation system comprises: cumulative beam charge quantity measurement means which measures a cumulative beam charge quantity (Qmeas) in the synchrotron; target current setting means which sets a target beam current value (Ifb) for beam current extracted from the synchrotron based on the cumulative beam charge quantity (Qmeas) measured by the cumulative beam charge quantity measurement means; and extraction beam current correction control means which controls the beam current based on the target value (Ifb) of the extraction beam current determined by the target current setting means.

[0009]

According to the present invention, a particle beam irradiation system and a charged particle beam correction method can be provided that are capable of enhancing the

beam utilization efficiency without deteriorating the irradiation dose uniformity.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]

Fig. 1 is a schematic block diagram showing the configuration of a particle beam irradiation system in accordance with an embodiment of the present invention.

Fig. 2A is a graph showing the change in the energy of a circulating beam during the operation cycle of a synchrotron in accordance with the embodiment of the present invention.

Fig. 2B is a graph showing the change in the cumulative beam charge quantity during the operation cycle of the synchrotron in accordance with the embodiment of the present invention.

Fig. 3 is a schematic diagram showing the configuration of an irradiation device employed in the embodiment.

Figs. 4A - 4C are schematic diagrams showing beam scan paths in the uniform scanning irradiation method.

Fig. 5 is a flow chart showing a control preparation flow before the start of irradiation control in accordance with the embodiment of the present invention.

Fig. 6 is a flow chart showing the flow of the beam irradiation control in accordance with the embodiment of the present invention.

Fig. 7 is a graph showing time-variations of a target beam current value and the cumulative beam charge quantity (accompanying the change in the target beam current value) in the beam irradiation control according to the beam irradiation control flow in accordance with the embodiment of the present invention.

Fig. 8 is a schematic block diagram showing the configuration of a feedback control system for extraction beam current in accordance with the embodiment of the present invention.

Fig. 9 is a flow chart showing a beam irradiation control flow further including advancement irradiation control in accordance with another embodiment of the present invention.

Fig. 10 is a schematic block diagram showing time-variations of the target beam current value and the cumulative beam charge quantity (accompanying the change in the target beam current value) in the beam irradiation control according to the beam irradiation control flow further including the advancement irradiation control in accordance with the embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0011]

A particle beam irradiation device used for particle therapy generally comprises an ion beam generating device, a beam transport system and an irradiation device. The ion beam generating device includes a synchrotron or a cyclotron

for accelerating the ion beam circulating along an orbit up to a desired energy level.

[0012]

The synchrotron includes a radio-frequency accelerator (acceleration cavity) for accelerating the ion beam circulating along the orbit up to a target energy level by applying radio-frequency voltage to the ion beam, an extraction radio-frequency electrode for enhancing the betatron oscillation amplitude of the circulating ion beam, and an extraction deflector for extracting the ion beam from the orbit (see the Patent Literature 1, for example). When the ion beam accelerated to the target energy level is extracted from the synchrotron to the beam transport system, a radio-frequency magnetic field or a radio-frequency electric field (hereinafter referred to as a "radio-frequency signal") is applied to the extraction radio-frequency electrode and the betatron oscillation amplitude (amplitude of the proper oscillation of the circulating ion beam) is enhanced. The ion beam with the enhanced betatron oscillation amplitude is moved to the outside of the stability limit, extracted from the synchrotron to the beam transport system, and transported to the irradiation device.

[0013]

The irradiation device shapes the ion beam lead from the ion beam generating device in conformity with the shape of the target volume (affected part) and the depth of the target volume from the patient's body surface and irradiates the target volume of the patient on the treatment bed.

Selectable irradiation methods include the uniform scanning irradiation method (see Fig. 1 on page 3561 of the Non-patent Literature 1).

[0014]

The uniform scanning irradiation method scans the ion beam on the irradiation plane with the scanning electromagnets, and thus the energy loss in the method is smaller than that in a double scatterer irradiation system which spreads the beam to the entire area of the irradiation plane by using two types of scatterers. Therefore, the uniform scanning irradiation method has the characteristic that the propagation range of the ion beam can be made longer compared to the double scatterer irradiation method.

[0015]

A uniform scanning irradiation device comprises two scanning electromagnets (horizontal scanning electromagnet, vertical scanning electromagnet) for scanning the ion beam on the irradiation plane, an energy absorber for shaping the ion beam scanned by the scanning electromagnets and thereby forming an absorbed-dose range (Spread-Out Bragg Peak, hereinafter referred to as an "SOBP") adapted to the thickness of the target volume in the depth direction, and a bolus and a collimator for forming an irradiation field in conformity with the target shape (tumor shape). In such uniform scanning irradiation devices, a ridge filter (see Fig. 31 on page 2078 of the Non-patent Literature 2) is used for the energy absorber for forming the SOBP. The ridge filter is a structure formed by arranging a plurality of

wedge-shaped energy absorbers (differing in the thickness of the region through which the ion beam passes) on a plane. The energy of a beam passing through the ridge filter is attenuated depending on the thickness of each transmitting region of the ridge filter. The SOBP is formed by the superposition of the attenuated ion beams.

[0016]

In the uniform scanning irradiation method, a prescribed level of dose uniformity is achieved by performing multiple times of repetitive irradiation with the ion beam (scans on the irradiation plane) while keeping the beam current at a low level (hereinafter referred to as "repaint") as described also in the Non-patent Literature 2. Since the deterioration in the dose uniformity on the irradiation plane can be suppressed by controlling the beam current at a constant level, it is possible with this method to reduce the number of times of repaint and increase the dose rate.

[0017]

Beam scanning methods in the uniform scanning irradiation method will be explained below referring to Figs. 4A - 4C. The single circle wobbler method (described in the Patent Literature 2, for example), the spiral wobbler method (described in the Patent Literature 3, for example), the raster scan method (see Fig. 7 on page 3564 of the Non-patent Literature 1), and the line scan method have been proposed for the uniform scanning irradiation method. In the single circle wobbler method, the irradiating beam is

scanned with the scanning electromagnets along a single circle as shown in Fig. 4A and high dose uniformity is achieved through the superposition of Gaussian distribution of the scanned beam. The spiral wobbler method (unshown) is a scanning method devised for increasing the beam utilization efficiency while securing the propagation range in comparison with the single circle wobbler method. The scan on the irradiation plane is implemented by superposition of scan loci having different initial phases. In the raster scan method, the beam is scanned successively along straight lines as shown in Fig. 4B differently from the above wobbler methods. In the line scan method, the beam irradiation is stopped during the scans in the short-scan directions (differently from the raster scan method) as shown in Fig. 4C and the effective beam utilization efficiency is increased.

[0018]

Here, a beam scan necessary for the one-unit irradiation will be explained. First, a beam scan range necessary for the one-unit irradiation means the locus of a scan from a scan starting point to a scan ending point. As shown in Fig. 4A, the scan starting point and the scan ending point are the same point in the single circle wobbler method and the spiral wobbler method (unshown). In the raster scan method and the line scan method shown in Figs. 4B and 4C, the scan ending point differs from the scan starting point. The scan time necessary for each of these one-unit irradiations is approximately several tens to 100

milliseconds per scan, which is sufficiently shorter than the extraction control time of the synchrotron (approximately 0.5 to several seconds).

[0019]

Next, matters needing examination will be explained below by using descriptions in the literatures. In order to maintain the uniformity of the irradiation dose in the uniform scanning irradiation method, it is desirable that the irradiation of a prescribed area during the extraction control be continued until the completion of the irradiation without exhausting the beam. In the Non-patent Literature 1, a cyclotron is employed as the ion beam generating device. In the case of a cyclotron, the ion beam supplied to the irradiation device is a direct-current beam. In contrast, when a synchrotron is employed as the ion beam generating device, an ion beam accumulated in the synchrotron in sync with each operation cycle of the synchrotron is supplied to the irradiation device. Therefore, the continuation of the extraction control can lead to the exhaustion of the ion beam accumulated in the synchrotron. In case of exhaustion of the ion beam accumulated in the synchrotron, it is necessary to stop the extraction control and the beam scan control of the scanning electromagnets and thereafter continuously perform the accumulation and extraction control of the ion beam and the beam scan control of the scanning electromagnets again from the next operation cycle.

[0020]

In order to prevent the dose uniformity from being affected even in case of the beam irradiation stoppage due to the exhaustion of the cumulative beam charge quantity (quantity of the accumulated electric charge of the ion beam), the electric current value of the ion beam supplied from the synchrotron to the irradiation device is set low and the repaint is executed approximately 100 times, by which the dose uniformity deterioration at the position of the beam irradiation stoppage is suppressed (description on page 3562 of the Non-patent Literature 1). Since the irradiation with a prescribed dose takes a long time as explained above, the treatment time is necessitated to be long.

[0021]

Meanwhile, extraction beam current feedback control has been devised as a measure to suppress time-fluctuation of the ion beam supplied from the synchrotron. In the extraction beam current feedback control, an ionization electric charge quantity detected by a dose monitor or the like in the irradiation device is converted into an electric current value of the ion beam. The electric current value of the ion beam extracted from the synchrotron (extraction beam current value) is corrected to a desired beam current value by correcting the amplitude value of the extraction radio-frequency voltage by use of the deviation (difference) between the detected electric current value (acquired by the conversion) and a target electric current value (target beam current value). When the extraction beam current feedback

control is employed for the uniform scanning irradiation method, the feedback control is performed by setting the target beam current value at a constant value. However, it is known that the electric charge quantity of the ion beam accumulated in the synchrotron fluctuates due to electric current fluctuation of the ion beam supplied from the preaccelerator to the synchrotron. Thus, if the ion beam charge quantity (ion beam electric charge quantity) accumulated in the synchrotron during the extraction beam current feedback control falls below an extraction beam charge quantity (product of the time necessary for the one-unit irradiation and the target current value of the extracted beam), a chip can occur in the beam current waveform in the latter half of the extraction control and the dose uniformity can deteriorate due to the exhaustion of the cumulative beam charge quantity even with the extraction beam current feedback control.

[0022]

A method for suppressing the beam exhaustion during the extraction control has been described in JP, A 2010-238463 (hereinafter referred to as "Patent Literature 4"). In this method, the cumulative beam charge quantity is measured after the extraction control of the beam from the synchrotron. If the cumulative beam charge quantity is less than the electric charge quantity necessary for the one-unit irradiation, the control shifts the deceleration control. Such control prevents the beam exhaustion during the one-unit irradiation; however, the utilization efficiency of the

beam charge quantity accumulated in the synchrotron is deteriorated.

[0023]

In a method described in Japanese Patent No. 4691583 (hereinafter referred to as "Patent Literature 5"), the target value of the extraction beam current feedback control is corrected by measuring the cumulative beam charge quantity before the extraction control. For the correction of the target value of the feedback control, a standard value of the cumulative electric charge quantity of the ion beam circulating in the synchrotron is set previously. The extraction beam current value is corrected based on the result of comparison between the cumulative beam charge quantity measured just before the extraction control of the synchrotron and the standard value of the cumulative electric charge quantity. Since the Patent Literature 5 assumes efficient extraction of the accumulated ion beam charge (cumulative beam charge quantity) within one extraction control, no irradiation methods like the uniform scanning irradiation method (setting the electric current value of the ion beam supplied to the irradiation device at a low level and performing the scan/irradiation multiple times separately) have been presumed.

[0024]

In each embodiment of the present invention described below, even in case of fluctuation in the cumulative beam charge quantity in the synchrotron, the beam exhaustion during the one-unit irradiation can be prevented while also

securing the uniformity of the irradiation dose. Further, through efficient use of the cumulative beam charge quantity in the synchrotron, the time necessary for the irradiation with a prescribed dose can be reduced and the treatment time can be shortened.

[0025]

Incidentally, each of the embodiments described below is about the uniform scanning irradiation method in which the irradiation device performs the one-unit irradiation multiple times. Performing the one-unit irradiation multiple times (i.e., performing the repaint) typically means repeating one-plane irradiation of a certain irradiation plane (irradiation area) multiple times. In each embodiment, the "one-plane irradiation" performed in the uniform scanning irradiation method is expressed as "one-unit irradiation". This is for clarifying the difference from methods (like that of the Patent Literature 5) performing the one-plane irradiation with the ion beam accumulated in the synchrotron only once.

<First Embodiment>

[0026]

A particle beam irradiation system in accordance with a preferred embodiment of the present invention will be described below with reference to Figs. 1 - 3. As shown in Fig. 1, the particle beam irradiation system 1 of this embodiment comprises an ion beam generating device 11, a beam transport system 14 and an irradiation field formation device (charged particle beam irradiation device,

hereinafter referred to as an "irradiation device") 30. The beam transport system 14 connects the ion beam generating device 11 to the irradiation device 30 installed in a treatment room.

[0027]

A control system of the particle beam irradiation system 1 includes an accelerator controller 40, a centralized controller 41, a treatment planning device 43, a storage device 42, a timing system 50 and an interlock system 60. The accelerator controller 40 controls the ion beam generating device 11 and the beam transport system 14. The centralized controller 41 has centralized control of the whole particle beam irradiation system 1. The treatment planning device 43 plans beam irradiation conditions for the patients. The storage device 42 stores information on the beam irradiation conditions planned by the treatment planning device 43, control information on a synchrotron 13 (ion beam generating device) and the beam transport system 14, etc. The timing system 50 realizes synchronous control of devices constituting the synchrotron 13. The interlock system 60 is provided independently of the centralized controller 41 in order to secure the safety of the patients. Further, an extraction controller 20 controls radio-frequency voltage used for the beam extraction from the ion beam generating device 11 to the beam transport system 14.

[0028]

The ion beam generating device 11 includes an ion source (unshown), a preaccelerator 12 and the synchrotron

13. The ion source is connected to the preaccelerator 12. The preaccelerator 12 is connected to the synchrotron 13. The preaccelerator 12 accelerates an ion beam 10 generated by the ion source up to an energy level at which the ion beam 10 can be injected to the synchrotron 13. The ion beam 10a accelerated by the preaccelerator 12 is injected to the synchrotron 13.

[0029]

Fig. 2A shows the change in the energy of the circulating beam during the operation cycle of the synchrotron 13. Fig. 2B shows the change in the cumulative beam charge quantity (cumulative beam electric charge quantity). The synchrotron 13 executes a sequence of operation control (injection, acceleration, extraction, deceleration) at prescribed cycles (2 - 3 seconds). For the extraction control, the synchrotron 13 previously executes extraction preparation control.

[0030]

The beam 10b injected to the synchrotron 13 is accelerated up to a desired energy level by receiving the energy of the radio-frequency voltage applied to the acceleration cavity (unshown). In this case, the magnetic field intensity of deflecting electromagnets 18, quadrupole electromagnets (unshown), etc. and the frequency of the radio-frequency voltage applied to the acceleration cavity are increased with the increase in the circulation energy of the ion beam 10b so that the orbit of the ion beam 10b circulating inside the synchrotron 13 remains constant.

[0031]

The ion beam 10b which has been accelerated up to the desired energy level undergoes the extraction preparation control, in which a condition enabling the extraction of the circulating beam 10b (stability limit condition of the circulating beam) is satisfied by controlling the magnitudes of excitation of the quadrupole electromagnets and sextupole electromagnets (unshown). After the extraction preparation control is finished, the extraction controller 20 applies radio-frequency voltage to an extraction radio-frequency electrode 16, by which the betatron oscillation amplitude of the beam 10b circulating inside the synchrotron 13 is increased. The circulating beam 10b exceeding the stability limit condition due to the increase in the betatron oscillation amplitude is extracted from the synchrotron 13 to the beam transport system 14 and then transported to the irradiation device 30. The beam extraction control from the synchrotron 13 can be implemented at high speed by the extraction controller 20 by performing ON/OFF control of the radio-frequency voltage applied to the extraction radio-frequency electrode 16.

[0032]

The cumulative beam charge quantity 70 in the synchrotron 13 changes as shown in Fig. 2B according to the operation sequence of the synchrotron 13 (Fig. 2A). The cumulative beam charge quantity is gradually increased by the injection of the ion beam 10a to the synchrotron 13. While the cumulative beam charge quantity attenuates in the

initial stage of the acceleration control due to ion beam loss caused by the space-charge effect, etc., the cumulative beam charge quantity remains substantially constant in the middle and late stages of the acceleration control. The synchrotron 13 emits the ion beam 10b in units of the electric charge quantity (Qscan) necessary for the one-unit irradiation. After each one-unit irradiation is finished, the beam emission (beam extraction) is stopped for preparations for the next irradiation (e.g., moving scanning electromagnets 32 (explained later) of the irradiation device 30 to an irradiation starting point). The emission (extraction) and the stoppage of the beam are repeated. The beam charge quantity (Qloss) remaining in the synchrotron 13 without being extracted during the extraction control period fades out to 0 due to the subsequent deceleration control for decelerating (reducing the energy of) the beam.

[0033]

Fig. 3 shows the configuration of the irradiation device. The irradiation device 30 executes the scan on the irradiation plane by using the scanning electromagnets 32 and successively checks the dose intensity and the beam shape of the irradiating beam 10d by using a dose monitor 31 (measuring the irradiation dose of the beam 10d applied to the patient) and a beam shape monitor (unshown). The beam 10d scanned by the scanning electromagnets 32 passes through an energy absorber 33 and thereby forms an SOBP adapted to the thickness of the target volume (affected part) in the depth direction. The beam with the SOBP is shaped by using

patient-specific devices (collimator 34, bolus 35, etc.) customized for the target shape 37 (the shape of the target volume) of the patient 36, by which an irradiation field in conformity with the target shape is formed.

[0034]

A method for controlling the extraction radio-frequency voltage with the extraction controller 20 will be explained below referring to Fig. 8. A radio-frequency oscillator 21 outputs a radio-frequency signal having a center frequency Fc for the extraction radio-frequency voltage which is controlled depending on the energy. The radio-frequency signal outputted from the radio-frequency oscillator 21 is mixed by a radio-frequency mixer 221 with a bandlimited radio-frequency signal outputted from a bandlimited radio-frequency signal generating unit 22, by which a bandlimited radio-frequency signal having a center frequency Fc and a frequency width 2Fw is formed. The amplitude value of the radio-frequency voltage is controlled in a beam current feedback control circuit 24 by the mixed bandlimited radio-frequency signal so as to implement a beam current intensity waveform (target value of beam current intensity) determined by a target beam current correction calculation unit 29. The beam current feedback control circuit 24 includes an amplitude modulator 23, feedback loop gain regulators 241 and 242, an adder circuit 243 and a radio-frequency switch 25. First, the feedback loop gain regulator 241 calculates the deviation of a dose monitor detection signal 311 (from the dose monitor 31 detecting the

irradiation dose) from a target beam current value (Ifb) set by the target beam current correction calculation unit 29. By using the result of the calculation (deviation), the feedback loop gain regulator 242 calculates a feedback correction signal based on a feedback gain. The adder circuit 243 corrects an amplitude modulation signal (Am) by adding the feedback correction signal to the amplitude modulation signal (Am). The result of the addition is set to the amplitude modulator 23, by which the beam current feedback control is implemented.

[0035]

The radio-frequency signal having the amplitude value controlled by the beam current feedback control circuit 24 is transmitted to a radio-frequency power amplifier 17 via a radio-frequency switch 26 controlled by the interlock system 60. The bandlimited radio-frequency signal amplified by the radio-frequency power amplifier 17 is applied to the extraction radio-frequency electrode 16. By the radio-frequency signal applied to the extraction radio-frequency electrode 16, the betatron oscillation amplitude of the beam 10b circulating in the synchrotron 13 is enhanced. The beam 10b with the enhanced betatron oscillation amplitude is extracted from the synchrotron 13 to the beam transport system 14.

[0036]

The method of the calculation of the target beam current by the target beam current correction calculation unit 29 constituting the extraction controller 20, as a

characteristic of this embodiment, will be explained below referring to Figs. 5, 6, 7 and 8. Fig. 5 shows a control preparation flow before the start of the irradiation control. Fig. 6 shows the flow of the beam irradiation control. Fig. 7 shows time-variations of the target beam current value and the cumulative beam charge quantity (accompanying the change in the target beam current value) in the beam irradiation control according to the beam irradiation control flow shown in Fig. 6. Fig. 8 shows the configuration of the feedback control system for the extraction beam current.

[0037]

A flow for calculating and setting the target beam current value to be used for the extraction beam current feedback control before the irradiation will be explained below referring to Fig. 5. First, a method for setting the initial value of the target beam current value (Ifb) to be used for the extraction beam current feedback control before the start of the irradiation treatment for the patient will be explained. The treatment planning device 43 calculates the total irradiation dose to the target volume of the patient 36 and registers the calculated total irradiation dose in the storage device 42. Conversion table data for the conversion between the irradiation dose and the irradiation electric charge quantity is prepared in the storage device 42. Based on irradiation conditions inputted from a treatment scheduler (unshown), the centralized controller 41 loads the total irradiation dose calculated by

the treatment planning device 43 and calculates a total irradiation electric charge quantity (Qtarget) necessary for achieving the total irradiation dose requested by the treatment planning device 43 by use of the conversion table data prepared in the storage device 42. The centralized controller 41 transmits the total irradiation electric charge quantity (Qtarget) and setting conditions for the irradiation device to an irradiation controller 44. A reception unit of the irradiation controller 44 receives the information including the total irradiation electric charge quantity (Qtarget).

[0038]

The irradiation controller 44 calculates a reference beam current value (Iscan) in the one-unit irradiation based on a beam current control range (control range of the beam current that can be extracted from the synchrotron 13) and sets a scan time (Tscan) necessary for the one-unit irradiation based on the scan speed of the scanning electromagnets 32 (801).

[0039]

Subsequently, the electric charge quantity (Qscan) necessary for the one-unit irradiation and the number of times of repaint (Nr) are calculated (802). The electric charge quantity necessary for the one-unit irradiation (Qscan) can be calculated by multiplying the reference beam current value (Iscan) in the one-unit irradiation by the scan time (Tscan) necessary for the one-unit irradiation as shown in the following expression (1): The number of times

of repaint (Nr) can be calculated by dividing the total irradiation electric charge quantity (Qtarget) by the electric charge quantity (Qscan) necessary for the one-unit irradiation as shown in the following expression (2):

[0040]

$$Q_{scan} = I_{scan} \cdot T_{scan} \quad \cdots (1)$$

[0041]

$$N_r = \frac{Q_{target}}{Q_{scan}} \quad \cdots (2)$$

[0042]

A remaining irradiation electric charge quantity (Qrest) for the irradiation area is initialized by setting it at the total irradiation electric charge quantity (Qtarget) (803). The remaining irradiation electric charge quantity (Qrest) is a quantity acquired by subtracting the cumulative value (accumulated value) of the electric charges of the ion beams that have been applied to the target volume (cumulative irradiation electric charge quantity (Qsum)) from the total irradiation electric charge quantity (Qtarget). The cumulative irradiation electric charge quantity (Qsum) is initialized by setting it at 0 (804).

[0043]

The reference beam current value (Iscan) in the one-unit irradiation is set to the extraction controller 20 as the initial value of the target beam current value (Ifb) of the extraction beam current feedback control (805). The above control flow (801 - 805) is executed by the

irradiation controller 44. Incidentally, the irradiation preparation control shown in Fig. 5 is executed only in the operation cycle at the start of the irradiation of the patient (not executed in the second and subsequent operation cycles).

[0044]

The beam irradiation control flow will be explained below referring to Fig. 6. The synchrotron 13 accelerates the beam injected from the preaccelerator 12 up to a prescribed energy level (811). After the beam acceleration control is finished, the cumulative beam charge quantity (Qmeas) as the amount of beam electric charge accumulated in the synchrotron 13 is measured (812). The cumulative beam charge quantity (Qmeas) is measured by using a cumulative beam charge quantity detecting unit 15 (cumulative beam charge quantity measurement means) (e.g., DCCT) arranged inside the synchrotron 13. The result of the measurement of the cumulative beam charge quantity (Qmeas) is loaded into the extraction controller 20 and steps described in the following control flow are executed by the target beam current correction calculation unit 29 of the extraction controller 20.

[0045]

The target beam current correction calculation unit 29 first judges whether the cumulative beam charge quantity (Qmeas) in the synchrotron 13 has already been exhausted or not (813). When the cumulative beam charge quantity (Qmeas)

has been exhausted (Qmeas ≤ 0), the process advances to the beam deceleration control (814).

[0046]

When the cumulative beam charge quantity (Qmeas) has not been exhausted (Qmeas > 0), the target beam current correction calculation unit 29 compares the remaining irradiation electric charge quantity (Qrest) with the cumulative beam charge quantity (Qmeas) and thereby determines an electric charge quantity to be set as a comparative electric charge quantity (Qcomp) (815). The comparative electric charge quantity (Qcomp) is an electric charge quantity to be used for reference in correction control of the reference beam current value (Iscan) in the one-unit irradiation which will be explained later. When the remaining irradiation electric charge quantity (Qrest) is larger than the cumulative beam charge quantity (Qmeas), the comparative electric charge quantity (Qcomp) is set at the cumulative beam charge quantity (Qmeas) (816). When the remaining irradiation electric charge quantity (Qrest) is less than or equal to the cumulative beam charge quantity (Qmeas), the comparative electric charge quantity (Qcomp) is set at the remaining irradiation electric charge quantity (Qrest) (817). In short, the comparative electric charge quantity (Qcomp) is set at the smaller one of the remaining irradiation electric charge quantity (Qrest) and the cumulative beam charge quantity (Qmeas).

[0047]

Subsequently, the target beam current correction calculation unit 29 compares the comparative electric charge quantity (Qcomp) with the electric charge quantity (Qscan) necessary for the one-unit irradiation (818). When the comparative electric charge quantity (Qcomp) is larger than or equal to the electric charge quantity (Qscan) necessary for the one-unit irradiation (Qcomp ≥ Qscan), the correction of the target beam current value (Ifb) as the target value of the extraction beam current feedback control is not conducted (819). When the comparative electric charge quantity (Qcomp) is less than the electric charge quantity (Qscan) necessary for the one-unit irradiation (Qcomp < Qscan), the target beam current value (Ifb) is corrected to be smaller than the reference beam current value (Iscan) in the one-unit irradiation (820).

[0048]

As above, the target beam current correction calculation unit 29 (serving as target current setting means) determines the target value (Ifb) of the beam current by the correction on the basis of the reference beam current value (Iscan) in the one-unit irradiation. This enables control that properly compensates for fluctuations in the beam current (caused by the preaccelerator 12) by means of the correction. In this embodiment, whether the electric charge quantity necessary for the one-unit irradiation has been accumulated in the synchrotron or not is checked successively before the execution of each one-unit irradiation. In case where the cumulative beam charge

quantity in the synchrotron is insufficient, the uniformity of the irradiation dose is secured by preventing the beam exhaustion during the one-unit irradiation by correcting and controlling the extraction beam current value.

[0049]

The target beam current value (Ifb) is determined by correcting the reference beam current value (Iscan) in the one-unit irradiation by use of the ratio of the comparative electric charge quantity (Qcomp) to the electric charge quantity (Qscan) necessary for the one-unit irradiation as shown in the following expression (3):

[0050]

$$I_{fb} = \frac{Q_{comp}}{Q_{scan}} \cdot I_{scan} \quad \cdots (3)$$

[0051]

As above, the comparative electric charge quantity (Qcomp) is used for the determination of the target beam current value Ifb (target value (Ifb) of the beam current) by the target beam current correction calculation unit 29 serving as the target current setting means, by which the beam current can be set properly so as to enhance the beam utilization efficiency without causing the beam exhaustion during the irradiation of one plane. The efficient use of the cumulative beam charge quantity in the synchrotron makes it possible to reduce the time necessary for the irradiation with a prescribed dose, and consequently, to shorten the treatment time. Since the prevention of the beam exhaustion during the one-unit irradiation enables an increase in the

beam current value in the one-unit irradiation and a decrease in the number of times of repaint, the time necessary for the irradiation with the prescribed dose can be reduced and the treatment time can be shortened.

[0052]

Based on the above target beam current value (Ifb), the extraction beam current feedback control is performed by the beam current feedback control circuit 24 (as a part of the extraction controller 20) and the beam extraction control from the synchrotron 13 to the irradiation device 30 is carried out (821). After the one-unit irradiation is finished, the electric charge quantity of the irradiation is added to the cumulative irradiation electric charge quantity (Qsum) (822). In this case, the cumulative irradiation electric charge quantity (Qsum) is determined (updated) by adding the product of the target beam current value (Ifb) and the one-unit scan time (Tscan) to the cumulative irradiation electric charge quantity (Qsum) as shown in the following expression (4): The remaining irradiation electric charge quantity (Qrest) is also updated accordingly (823). The remaining irradiation electric charge quantity (Qrest) is determined by subtracting the cumulative irradiation electric charge quantity (Qsum) from the total irradiation electric charge quantity (Qtarget) as shown in the following expression (5):

[0053]

$$Q_{sum} = Q_{sum} + (I_{fb} \cdot T_{scan}) \quad \cdots (4)$$

[0054]

$$Q_{rest} = Q_{target} - Q_{sum} \quad \cdots (5)$$

[0055]

Finally, the cumulative irradiation electric charge quantity (Qsum) is compared with the total irradiation electric charge quantity (Qtarget) (824). If the cumulative irradiation electric charge quantity (Qsum) has reached the total irradiation electric charge quantity (Qtarget) (Qsum ≥ Qtarget), the beam irradiation control is finished. If the cumulative irradiation electric charge quantity (Qsum) has not reached the total irradiation electric charge quantity (Qtarget) yet (Qsum < Qtarget), the process returns to the control flow (812) to continue the beam irradiation control.

[0056]

Here, the reason for the comparison between the remaining irradiation electric charge quantity (Qrest) and the cumulative beam charge quantity (Qmeas) shown in the control flow (815), as a characteristic of this embodiment, will be explained below.

[0057]

First of all, the cumulative beam charge quantity (Qmeas) falls below the electric charge quantity (Qscan) necessary for the one-unit irradiation in the latter half of the extraction control time (Text) of the synchrotron. If the extraction control is continued with the cumulative beam charge quantity (Qmeas) less than the electric charge quantity (Qscan) necessary for the one-unit irradiation, the

beam is exhausted before the completion of the one-unit irradiation and the dose uniformity in the irradiation area is deteriorated. Therefore, the conventional technology reduces the ill effect of the dose uniformity deterioration due to the beam exhaustion by decreasing the beam current value in the one-unit irradiation and setting the number of times of repaint (Nr) at a sufficiently large number. Consequently, it has been impossible to increase the dose rate and a long treatment time has been necessary.

[0058]

Further, in the final stage of the beam irradiation control, the remaining irradiation electric charge quantity (Qrest) decreases, that is, the cumulative irradiation electric charge quantity (Qsum) approaches the total irradiation dose (Qtarget) satisfying the necessary irradiation dose. In this state, the remaining irradiation electric charge quantity (Qrest) approaches the electric charge quantity (Qscan) necessary for the one-unit irradiation, and falls below Qscan depending on the progress of the irradiation control. In the conventional technology, the control shifts to the deceleration control when the cumulative beam charge quantity (Qmeas) has fallen below the electric charge quantity (Qscan) necessary for the one-unit irradiation as described in the Patent Literature 4. Thus, the cumulative beam charge quantity (Qmeas) less than the electric charge quantity (Qscan) necessary for the one-unit irradiation undergoes the deceleration without being used for the irradiation. Consequently, the enhancement of the

beam utilization efficiency has been difficult in the conventional technology.

[0059]

To deal with these circumstances, the correction of the target beam current value (Ifb) (820) in the extraction beam current feedback control in this embodiment is made by using the smaller one of the remaining irradiation electric charge quantity (Qrest) and the cumulative beam charge quantity (Qmeas) as the comparative electric charge quantity (Qcomp). Since the dose rate can be increased along with the enhancement of the beam utilization efficiency while also satisfying the dose uniformity, the treatment time can be shortened.

[0060]

The time-variations of the target beam current value and the cumulative beam charge quantity (accompanying the change in the target beam current value) in the beam irradiation control according to the above beam irradiation control flow will be explained below referring to Fig. 7. This embodiment is illustrating a case where the extraction control is executed by measuring the cumulative beam charge quantity (Qmeas) five times during the extraction control time (Text), and thus the remaining irradiation electric charge quantity (Qrest) is assumed to be sufficiently large.

[0061]

After the acceleration control of the synchrotron 13 is finished, the cumulative beam charge quantity ((a) in Fig. 7) is measured in response to a cumulative beam charge

quantity check signal 501 (Fig. 7(b)) by using the cumulative beam charge quantity detecting unit 15 installed in the synchrotron 13. At this point, the cumulative beam charge quantity equals Qmeas1. Since the comparative electric charge quantity (Qcomp) is set at Qmeas1 which is larger than the electric charge quantity (Qscan) necessary for the one-unit irradiation, the correction of the target beam current value (Ifb) is not conducted. Thus, the target beam current value ((c) in Fig. 7) is set at the reference beam current value (Iscan) in the one-unit irradiation (default value).

[0062]

In response to a beam extraction control signal ((d) in Fig. 7), the extraction control based on the extraction beam current feedback control is started. Accordingly, the beam 10d at a constant current is supplied to the irradiation device 30 and a beam current value (Idose) converted from the detection signal of the dose monitor 31 is observed ((e) in Fig. 7). After the beam irradiation for the one-unit scan time (Tscan) is finished, the beam extraction control is stopped and the cumulative beam charge quantity (Qmeas) is measured again. In this embodiment, the sequence from the beam measurement and the extraction control is repeated in the same way three times (Qmeas2 - Qmeas4).

[0063]

In response to the fifth cumulative beam charge quantity check signal 501, the cumulative beam charge

quantity (Qmeas) is measured. At this point, the cumulative beam charge quantity equals Qmeas5. Since the comparative electric charge quantity (Qcomp) is set at Qmeas5 which is smaller than the electric charge quantity (Qscan) necessary for the one-unit irradiation, the correction of the target beam current value (Ifb) is necessary. Therefore, the target beam current value (Ifb) is set lower than the reference beam current value (Iscan) in the one-unit irradiation by correcting the target beam current value (Ifb) according to the expression (3). By executing the extraction control based on the extraction beam current feedback control by using the corrected target beam current value (Ifb), the beam current value (Idose) converted from the dose monitor detection signal is used for the beam irradiation.

[0064]

Next, an operating method of the particle beam irradiation device in accordance with this embodiment will be described below referring to Fig. 8. The doctor inputs patient information (position and size of the target volume, beam irradiation direction, and maximum irradiation depth) to the treatment planning device 43. Based on the inputted patient information, the treatment planning device 43 (employing treatment planning software) calculates the SOBP width, the irradiation field size, the target dose for the target volume, etc. necessary for the treatment.

[0065]

The results of the calculations by the treatment planning device 43 are stored in the storage device 42. The centralized controller 41 transmits the total irradiation electric charge quantity (Qtarget) and the irradiation conditions to the irradiation controller 44 based on the irradiation conditions inputted from the treatment scheduler (unshown). The irradiation controller 44 selects setting conditions of devices constituting the irradiation device and accordingly transmits the total irradiation electric charge quantity (Qtarget), the reference beam current value (Iscan) in the one-unit irradiation, the scan time (Tscan) necessary for the one-unit irradiation, the electric charge quantity (Qscan) necessary for the one-unit irradiation, the number of times of repaint (Nr), etc. to the extraction controller 20. The calculations of the electric charge quantity (Qscan) necessary for the one-unit irradiation, etc. characteristic of this embodiment are executed by the irradiation controller 44 based on the information from the treatment planning device 43.

[0066]

Treatment plan information is displayed on a display device (unshown) arranged in a control booth of the treatment room in preparation for the treatment. The radiologist checks information displayed on the display screen and arranges an energy absorber 33 specified by the display in the irradiation device 30.

[0067]

A treatment bed controller (unshown) moves the treatment bed (on which the patient has been fixed by the radiologist) according to instructions from the centralized controller 41 and positions the treatment bed so that the target volume (affected part) of the patient (target of irradiation) is situated on the extension of the beam axis.

[0068]

The accelerator controller 40 determines the irradiation beam energy and sets operation control parameters of devices constituting the synchrotron 13 and the beam transport system 14 based on the treatment plan information supplied from the centralized controller 41. For the extraction controller 20, the accelerator controller 40 sets the center frequency Fc, the frequency width Fw, amplitude modulation data Am and feedback gain Gfb (operation control parameters in regard to the extraction radio-frequency signal) corresponding to the energy of the extracted beam.

[0069]

The doctor issues an irradiation start signal (instruction) to the centralized controller 41 through the control panel of the aforementioned control booth. In response to the irradiation start instruction, the preaccelerator 12 accelerates the ion beam (e.g., protons (or heavy ions such as carbon ions)) generated from the ion source and supplies the accelerated ion beam to the synchrotron 13.

[0070]

The synchrotron 13 accelerates the ion beam 10a injected from the preaccelerator 12 up to a desired energy level while circulating the ion beam therein. After the ion beam 10b has been accelerated up to the targeted beam energy level, the cumulative beam charge quantity detecting unit 15 measures the cumulative beam charge quantity (Qmeas) in response to the cumulative beam charge quantity check signal 501 from the timing system 50. Based on the cumulative beam charge quantity (Qmeas), the target beam current correction calculation unit 29 sets the target beam current value (Ifb) of the extraction beam current feedback control circuit 24. Thereafter, in response to the beam extraction control signal 502 outputted from the timing system 50, the extraction radio-frequency signal is applied to the extraction radio-frequency electrode 16 and the beam controlled based on the target beam current value (Ifb) is extracted from the synchrotron 13.

[0071]

In the detection of the cumulative beam charge quantity (Qmeas) in this embodiment, the cumulative beam charge quantity corresponding to the first one-unit irradiation is detected in response to the cumulative beam charge quantity check signal 501 outputted from the timing system 50. The cumulative beam charge quantity check signal 501 for the next and subsequent units is detected based on a signal calculated by the extraction controller 20 from the one-unit scan time (Tscan) and an irradiation stoppage time (Toff) and having its starting point at the input time of

the beam extraction control signal 502 supplied from the timing system 50. However, the same effects can be achieved even if a device for generating the cumulative beam charge quantity check signals 501 corresponding to all the irradiation planes is provided outside the extraction controller 20 (e.g., in the irradiation controller 44).

[0072]

In the beam extraction control in this embodiment, the supply of the beam from the synchrotron 13 to the irradiation device 30 is stopped (suspended) during the irradiation stoppage time (Toff) between the one-unit irradiations (i.e., between successive units of irradiation) by inputting the beam extraction control signal 502 from the timing system 50 to the extraction controller 20 and making the target beam current correction calculation unit 29 open the radio-frequency switch 25 according to the beam extraction control signal (252 in the extraction controller 20) each time the one-unit irradiation is finished.

[0073]

The ion beam 10c extracted from the synchrotron 13 passes through the beam transport system 14 and arrives at the irradiation device 30. The ion beam 10d further proceeding along the beam path inside the irradiation device 30 is scanned by the scanning electromagnets 32, shaped by the energy absorber 33 to form the SOBP, and then applied to the target volume of the patient.

[0074]

The dose of the ion beam applied to the target volume is measured by the dose monitor 31. The detection signal 311 from the dose monitor 31 is inputted to the extraction beam current feedback control circuit 24. The beam current feedback control circuit 24 controls the extraction beam current at a constant value by executing the feedback correction to the amplitude control value of the radio-frequency voltage based on the deviation (difference) between the target beam current value (Ifb) and the beam current value (Idose) detected by the dose monitor 31.

[0075]

After the completion of the one-unit irradiation of the target volume, the beam extraction control is stopped, the excitation levels of the scanning electromagnets are returned to their irradiation start positions, and the cumulative irradiation electric charge quantity (Qsum) is recorded. Thereafter, the cumulative beam charge quantity (Qmeas) is measured, the target beam current value (Ifb) is corrected based on the result of the measurement, and the one-unit irradiation is started again. The beam irradiation is carried out by repeating the above control until the cumulative irradiation electric charge quantity (Qsum) reaches the total irradiation electric charge quantity (Qtarget).

[0076]

Incidentally, when some kind of failure hindering the beam irradiation of the patient has occurred to a device constituting the particle beam irradiation system 1 during

the irradiation control, the interlock system 60 outputs a signal indicating that a device is in an abnormal state (abnormality signal 601) to the centralized controller 41 and to the interlocking radio-frequency switch 26 of the extraction controller 20 in parallel. The extraction controller 20 receives the abnormality signal 601 from the interlock system 60 as a beam extraction stop instruction and immediately opens the interlocking radio-frequency switch 26, by which the application of the extraction radio-frequency signal to the radio-frequency electrode 16 is stopped. By the above operation, the synchrotron 13 realizes the interlock control for stopping the extraction (emission) of the ion beam 10b.

[0077]

According to this embodiment, the following effects can be achieved.

[0078]

(1) In this embodiment, a range from an irradiation starting position to an irradiation ending position in an irradiation area is handled as one unit of scan range (one-unit scan range), and the one-unit scan range is managed as an irradiation unit. Before the start of the beam irradiation of each one-unit scan range, the cumulative beam charge quantity (Qmeas) in the synchrotron 13 is measured and the target beam current value (Ifb) of the extraction beam current feedback control circuit 24 is corrected by the target beam current correction calculation unit 29 depending on the relationship between the cumulative beam charge

quantity (Qmeas) and the electric charge quantity (Qscan) necessary for the one-unit irradiation, by which the electric current value of the beam extracted from the synchrotron 13 (extraction beam current value) is controlled. By this control, the exhaustion of the cumulative beam charge quantity (Qmeas) in the synchrotron 13 during the one-unit irradiation can be prevented.

[0079]

(2) In this embodiment, the beam exhaustion does not occur in the irradiation of one plane (one irradiation area) since the cumulative beam charge quantity (Qmeas) in the synchrotron 13 is measured and the target beam current value (Ifb) of the extraction beam current feedback control is corrected based on the result of the measurement before the start of each one-plane irradiation as described above. This eliminates the need of setting the target beam current value (Ifb) of the extraction beam current feedback control at a low value as in the conventional technology in consideration of the deterioration in the dose uniformity caused by the exhaustion of the cumulative beam charge quantity (Qmeas) in the middle of the one-plane irradiation. Thus, according to this embodiment, the target beam current value (Ifb) of the extraction beam current feedback control in the one-plane irradiation can be increased, the dose rate can be raised, and consequently, the treatment time can be shortened.

[0080]

(3) In this embodiment, successive monitoring of the exhaustion of the cumulative beam charge quantity 70 is unnecessary and the processes for stopping the beam extraction control and the beam scan control in response to the exhaustion of the cumulative beam charge quantity 70 are made unnecessary. Therefore, the configurations and the control methods of the controllers constituting the particle beam irradiation system can be simplified. In systems successively monitoring whether the cumulative beam charge quantity 70 in the synchrotron 13 has been exhausted or not during the one-plane irradiation, the extraction control of the beam 10b is stopped along with stopping the beam scan control with the scanning electromagnets 32 in case of exhaustion of the beam 10b. Thereafter, it is necessary to perform the beam injection/acceleration again with the synchrotron 13 and then restart the beam extraction control of the synchrotron 13 and the beam scan control of the scanning electromagnets 32.

<Second Embodiment>

[0081]

A second embodiment of the present invention will be described below. While the device configuration in this embodiment is equivalent to that in the first embodiment, the correction method of the target beam current correction calculation unit 29 for correcting the target beam current value (Ifb) differs from that in the first embodiment.

[0082]

The beam irradiation control flow in this embodiment will be explained below referring to Fig. 9. This flow differs from the flow shown in Fig. 6 in that advancement correction control of the target beam current value (Ifb) based on a advancement irradiation electric charge quantity (Qcarry) (825 - 828 in Fig. 9) is employed instead of the correction control of the target beam current value (Ifb) based on the comparative electric charge quantity (Qcomp) in the first embodiment (818 - 820 in Fig. 6).

[0083]

In the first embodiment, the cumulative beam charge quantity (Qmeas) gradually decreases with the passage of the extraction control time (Text) of the synchrotron. In the latter half of the extraction control time (Text), the cumulative beam charge quantity (Qmeas) can become extremely small compared to the electric charge quantity (Qscan) necessary for the one-unit irradiation. This similarly holds for the remaining irradiation electric charge quantity (Qrest) gradually decreasing with the progress of the irradiation control. In these cases, it becomes necessary to perform the beam irradiation with a small amount of electric charge. Thus, the need of performing one unit of irradiation control arises in order to efficiently utilize the cumulative beam charge quantity (Qmeas) or to satisfy the total irradiation electric charge quantity (Qtarget).

[0084]

Such a process occurs on each operation cycle of the synchrotron in cases where the cumulative beam charge

quantity (Qmeas) in the synchrotron 13 after the end of the acceleration control is not equal to an integral multiple of the electric charge quantity (Qscan) necessary for the one-unit irradiation.

[0085]

Therefore, the advancement irradiation electric charge quantity (Qcarry) shown in the following expression (6) is calculated in this embodiment (825 in Fig. 9) after the setting of the comparative electric charge quantity (Qcomp) (815 - 817 in Fig. 9).

[0086]

$$Q_{carry} = Q_{comp} - Q_{scan} \quad \cdots (6)$$

[0087]

The advancement irradiation electric charge quantity (Qcarry) in the expression (6) equals the difference between the comparative electric charge quantity (Qcomp) and the electric charge quantity (Qscan) necessary for the one-unit irradiation. This advancement irradiation electric charge quantity (Qcarry) is compared with the electric charge quantity (Qscan) necessary for the one-unit irradiation (826).

[0088]

When the advancement irradiation electric charge quantity (Qcarry) is less than or equal to the electric charge quantity (Qscan) necessary for the one-unit irradiation ($Qcarry \leq Qscan$), the advancement correction of the target beam current value (Ifb) is not conducted (827).

When the advancement irradiation electric charge quantity (Qcarry) is larger than the electric charge quantity (Qscan) necessary for the one-unit irradiation (Qcarry > Qscan), the advancement correction of the target beam current value (Ifb) is conducted as shown in the following expression (7) (828):

[0089]

$$I_{fb} = \frac{Q_{carry}}{T_{scan}} \quad \cdots (7)$$

[0090]

The advancement irradiation electric charge quantity (Qcarry) is acquired by further subtracting the electric charge quantity (Qscan) necessary for the one-unit irradiation from the comparative electric charge quantity (Qcomp) used in the first embodiment for the judgment on the correction of the target current value (Ifb). Through the two times of subtraction of the electric charge quantity (Qscan) necessary for the one-unit irradiation, in cases where the cumulative beam charge quantity (Qmeas) is less than twice the electric charge quantity (Qscan) necessary for the one-unit irradiation, reduction of the irradiation time can be realized by using the cumulative beam charge quantity (Qmeas) for one time of irradiation all at once and in advance.

[0091]

The above method can also be expressed as comparison between twice the electric charge quantity (Qscan) necessary for the one-unit irradiation and the comparative electric

charge quantity (Qcomp). When the comparative electric charge quantity (Qcomp) is less than twice the electric charge quantity (Qscan) necessary for the one-unit irradiation, the irradiation time can be reduced by means of the advancement irradiation, by correcting the target beam current value (Ifb) to be larger than the reference beam current value (Iscan) in the one-unit irradiation. Specifically, the cumulative beam charge quantity (Qmeas) divided by the scan time (Tscan) necessary for the one-unit irradiation is used as the target beam current value (Ifb) as shown in the expression (7).

[0092]

As above, appropriate control according to the cumulative beam charge quantity (Qmeas) is made possible by using the comparison value between the comparative electric charge quantity (Qcomp) and the electric charge quantity (Qscan) necessary for the one-unit irradiation as the criterion for the judgment on the necessity of the correction. Specifically, when the comparative electric charge quantity (Qcomp) is less than the electric charge quantity (Qscan) necessary for the one-unit irradiation as illustrated in the first embodiment, the control enhancing the beam efficiency while avoiding the beam exhaustion during the one-plane irradiation can be carried out. When the comparative electric charge quantity (Qcomp) is properly larger than the electric charge quantity (Qscan) necessary for the one-unit irradiation as illustrated in the second embodiment, the irradiation time can be shortened by means

of the advancement irradiation. It is also possible to employ criteria as a combination of the criterion in the first embodiment and the criterion in the second embodiment. In this case, the advantages of both embodiments can be enjoyed.

[0093]

Incidentally, while the comparative electric charge quantity (Qcomp) is compared with twice the electric charge quantity (Qscan) necessary for the one-unit irradiation in the second embodiment, similar effect can be achieved even when the multiplication factor of Qscan is not two, as long as the multiplication factor is larger than 1. The multiplication factor can be determined based on how much electric charge can be used for the irradiation in the one-unit irradiation. In cases where the cumulative beam charge quantity (Qmeas) in the synchrotron is a little larger than the electric charge quantity (Qscan) necessary for the one-unit irradiation in the latter half of the extraction control period, completing the beam irradiation by performing the irradiation once by means of irradiation electric charge quantity advancement makes it possible to reduce the time necessary for the irradiation with a prescribed dose and shorten the treatment time in comparison with separately performing the beam irradiation twice.

[0094]

The time-variations of the target beam current value and the cumulative beam charge quantity (accompanying the change in the target beam current value) in the beam

irradiation control according to the beam irradiation control flow in the second embodiment will be explained below referring to Fig. 10. For clarity of the explanation, the cumulative beam charge quantity (Qmeas1) just after the end of the acceleration control and the electric charge quantity (Qscan) necessary for the one-unit irradiation in Fig. 10 are assumed to be the same as those in Fig. 7.

[0095]

In Fig. 10, the advancement irradiation is not executed at the first to third measurement of the cumulative beam charge quantity (Qmeas1 - Qmeas3). The advancement irradiation is executed at the fourth measurement (Qmeas4) and the electric charge quantity used separately for two times of irradiation in Fig. 7 is used for one time of irradiation all at once and in advance. Therefore, the target beam current value (Ifb) in the fourth irradiation is set higher than the reference beam current value (Iscan) in the one-unit irradiation differently from the case of Fig. 7. Thereafter, the control shifts to the deceleration control without executing the fifth irradiation control. By this control, the irradiation time can be shortened by the sum total of the one-unit scan time (Tscan) and the irradiation stoppage time (Toff) between the one-unit irradiations.

[0096]

According to this embodiment, the small cumulative beam charge quantity (Qmeas) less than the electric charge quantity (Qscan) necessary for the one-unit irradiation,

occurring when the cumulative beam charge quantity (Qmeas) after the end of the acceleration control is not equal to an integral multiple of the electric charge quantity (Qscan) necessary for the one-unit irradiation, is used for the advancement irradiation, by which the shortening of the irradiation time can be realized. Since such an advancement process occurs on each operation cycle of the synchrotron, the irradiation time shortening effect is significant and further shortening of the treatment time can be realized.

[0097]

With this control, in cases where the cumulative beam charge quantity (Qmeas) in the synchrotron is a little larger than the electric charge quantity (Qscan) necessary for the one-unit irradiation in the latter half of the extraction control period, the beam irradiation can be completed by performing the irradiation once by means of irradiation electric charge quantity advancement in contrast to the first embodiment separately performing the beam irradiation twice. Consequently, the time necessary for the irradiation with a prescribed dose can be reduced and the treatment time can be shortened.

[0098]

In the particle beam irradiation system in each of the embodiments described above, the irradiation controller 44 calculates the beam current value (Iscan) necessary for the one-unit irradiation, the cumulative beam charge quantity detecting unit 15 (cumulative beam charge quantity measurement means) measures the cumulative beam charge

quantity (Qmeas) in the synchrotron, the target beam current correction calculation unit 29 (target current setting means) sets the target beam current value (Ifb) for the beam current extracted from the synchrotron 13 by correcting the beam current value (Iscan) necessary for the one-unit irradiation based on the cumulative beam charge quantity (Qmeas), and the extraction controller 20 (including extraction beam current correction control means) corrects the charged particle beam by controlling the beam current based on the target beam current value (Ifb). By the above correction of the charged particle beam, a particle beam irradiation system capable of enhancing the beam utilization efficiency without deteriorating the irradiation dose uniformity can be realized.

What is claimed is:

1. A particle beam irradiation system comprising a synchrotron in which an ion beam is accelerated and from which the ion beam is then extracted and an irradiation device for irradiating a target volume with the ion beam extracted from the synchrotron, the irradiation device performing one-unit irradiation multiple times, wherein the particle beam irradiation system comprises:

cumulative beam charge quantity measurement means which measures a cumulative beam charge quantity in the synchrotron;

target current setting means which sets a target beam current value for beam current extracted from the synchrotron based on the cumulative beam charge quantity measured by the cumulative beam charge quantity measurement means; and

extraction beam current correction control means which controls the beam current based on the target beam current value determined by the target current setting means.

2. The particle beam irradiation system according to claim 1, comprising:

reception means which receives information on a total irradiation electric charge quantity necessary for the multiple times of irradiation; and

an extraction controller which calculates a cumulative irradiation electric charge quantity,

wherein a comparative electric charge quantity, which is defined as the smaller one of the cumulative beam charge quantity and a remaining irradiation electric charge quantity calculated by subtracting the cumulative irradiation electric charge quantity from the total irradiation electric charge quantity, is used for the determination of the target beam current value by the target current setting means.

3. The particle beam irradiation system according to claim 2, comprising an irradiation controller which calculates an electric charge quantity necessary for the one-unit irradiation,

wherein the target current setting means uses a comparison value between the comparative electric charge quantity and the electric charge quantity necessary for the one-unit irradiation as a criterion for judgment on necessity of correction of the target beam current value.

4. The particle beam irradiation system according to claim 2 or 3, comprising an irradiation controller which calculates a beam current value necessary for the one-unit irradiation,

wherein the target current setting means determines the target beam current value based on the beam current

value necessary for the one-unit irradiation by means of correction.

5. The particle beam irradiation system according to any one of claims 2 - 4, wherein the target current setting means corrects the target beam current value to be smaller than a beam current value necessary for the one-unit irradiation when the comparative electric charge quantity is smaller than an electric charge quantity necessary for the one-unit irradiation.

6. The particle beam irradiation system according to claim 5, wherein the target beam current value is determined by correcting the beam current value necessary for the one-unit irradiation by use of the ratio of the comparative electric charge quantity to the electric charge quantity necessary for the one-unit irradiation.

7. The particle beam irradiation system according to any one of claims 2 - 6, wherein the target current setting means corrects the target beam current value to be larger than a beam current value necessary for the one-unit irradiation when the comparative electric charge quantity is smaller than twice an electric charge quantity necessary for the one-unit irradiation.

8. The particle beam irradiation system according to claim 7, wherein the target beam current value is determined

by dividing the cumulative beam charge quantity by a scan time necessary for the one-unit irradiation.

9. A charged particle beam correction method for a particle beam irradiation system equipped with a synchrotron in which an ion beam is accelerated and from which the ion beam is then extracted, and an irradiation device for irradiating a target volume with the ion beam extracted from the synchrotron, the irradiation device performing one-unit irradiation multiple times, comprising the steps of:

calculating a beam current value necessary for the one-unit irradiation by use of an irradiation controller;

measuring a cumulative beam charge quantity in the synchrotron by use of cumulative beam charge quantity measurement means;

setting a target beam current value for beam current extracted from the synchrotron by use of target current setting means by correcting the beam current value necessary for the one-unit irradiation based on the cumulative beam charge quantity; and

controlling the beam current based on the target beam current value by use of extraction beam current correction control means.