



(19) **United States**

(12) **Patent Application Publication**  
**IWATA et al.**

(10) **Pub. No.: US 2013/0253845 A1**  
(43) **Pub. Date: Sep. 26, 2013**

(54) **PARTICLE BEAM THERAPY SYSTEM**

(52) **U.S. Cl.**

(71) Applicant: **Mitsubishi Electric Corporation,**  
Chiyoda-ku (JP)

CPC ..... **A61B 5/48** (2013.01)  
USPC ..... **702/19**

(72) Inventors: **Takaaki IWATA,** Tokyo (JP); **Kengo Sugahara,** Tokyo (JP); **Hisashi Harada,** Tokyo (JP)

(57) **ABSTRACT**

(73) Assignee: **Mitsubishi Electric Corporation,**  
Chiyoda-ku (JP)

The objective is to eliminate the effect of the hysteresis of a scanning electromagnet and resume high-accuracy beam irradiation from an irradiation position where it has been interrupted, even in the case where emergency-stop processing is performed during therapy. There are provided an irradiation management apparatus that controls a scanning electromagnet; and an interlock information inputting device that generates an interlock signal for stopping irradiation of the charged particle beam, when a contingency occurs. When irradiation of the charged particle beam is resumed, the irradiation management apparatus performs idle operation in which the scanning electromagnet is controlled, with the charged particle beam unirradiated, from a start step, which is situated prior to a stop step and is different from the initial step in actual irradiation, to the stop step, and then irradiates the charged particle beam from the desired irradiation position coordinates corresponding to the stop step.

(21) Appl. No.: **13/897,085**

(22) Filed: **May 17, 2013**

**Related U.S. Application Data**

(62) Division of application No. 13/258,240, filed on Sep. 21, 2011, now Pat. No. 8,466,441, filed as application No. PCT/JP2011/053367 on Feb. 17, 2011.

**Publication Classification**

(51) **Int. Cl.**  
**A61B 5/00** (2006.01)

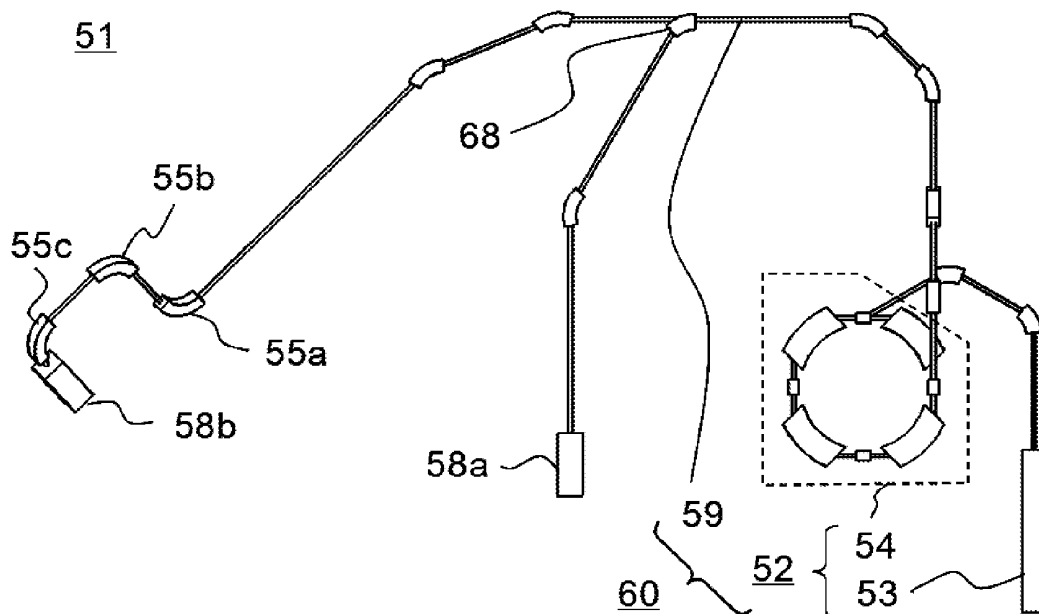


FIG. 1

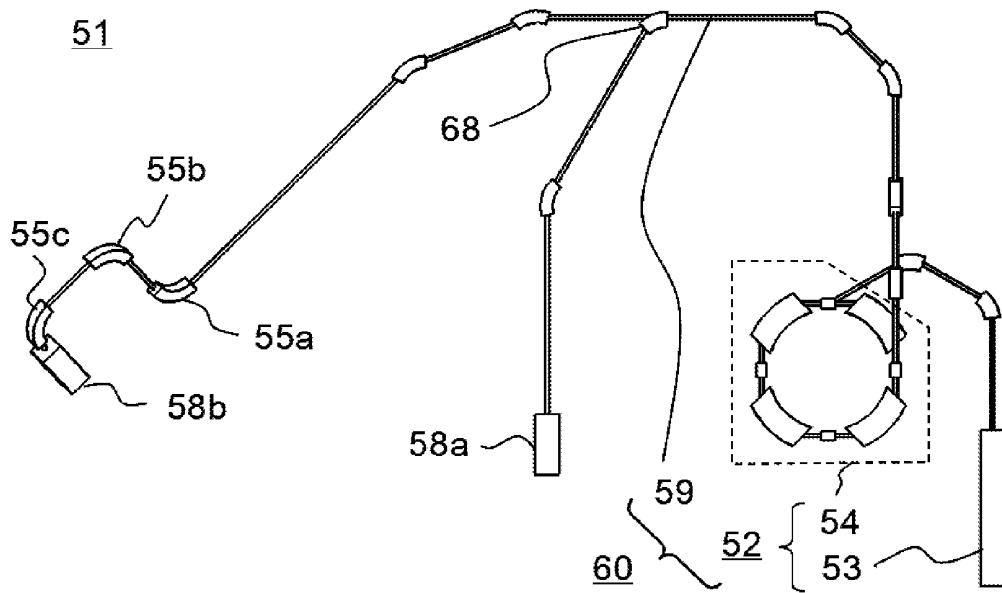


FIG. 2

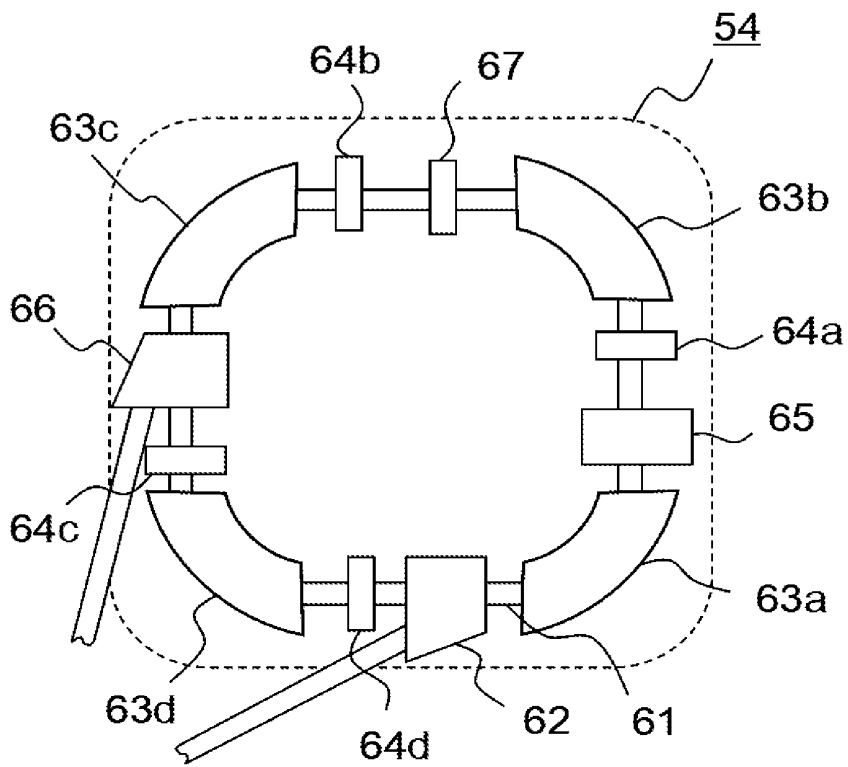




FIG. 4

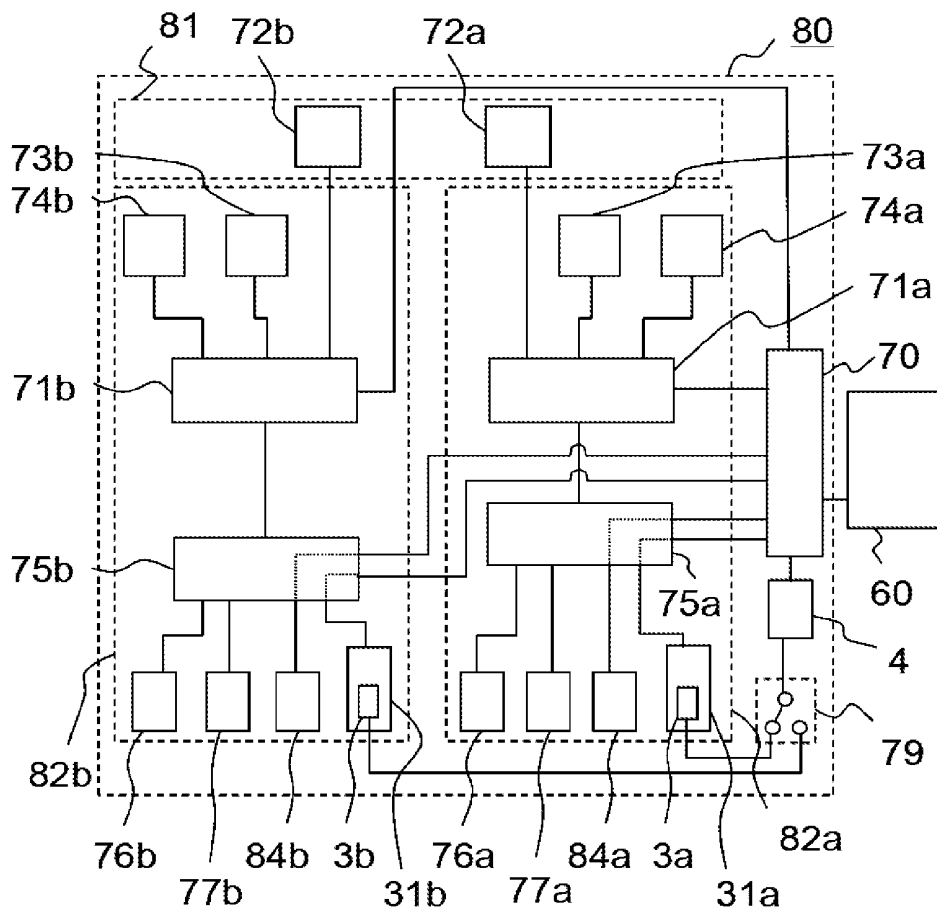


FIG. 5

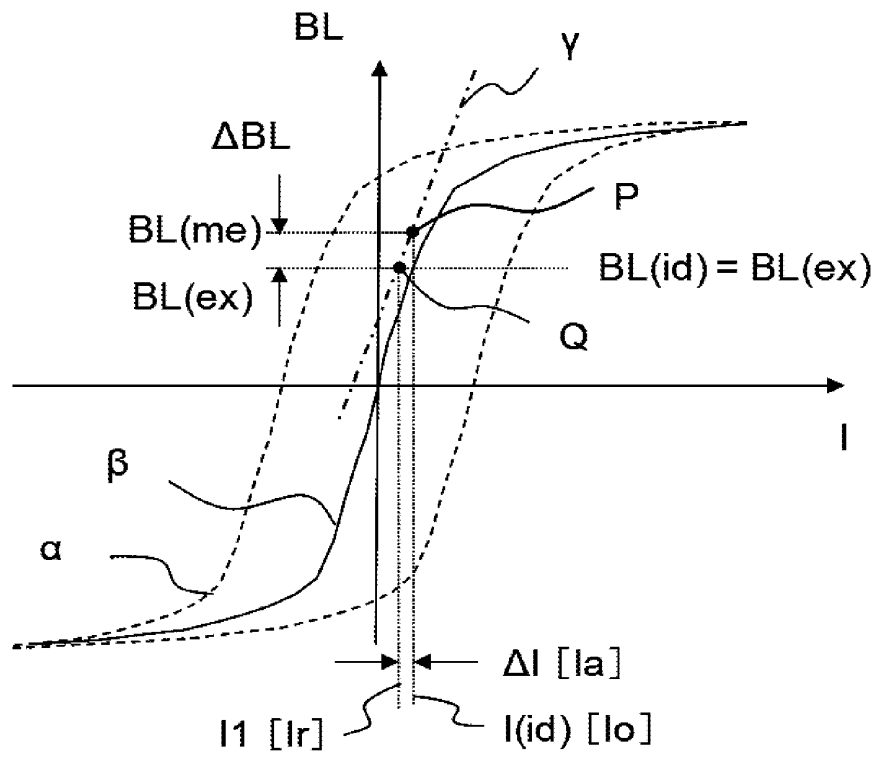


FIG. 6

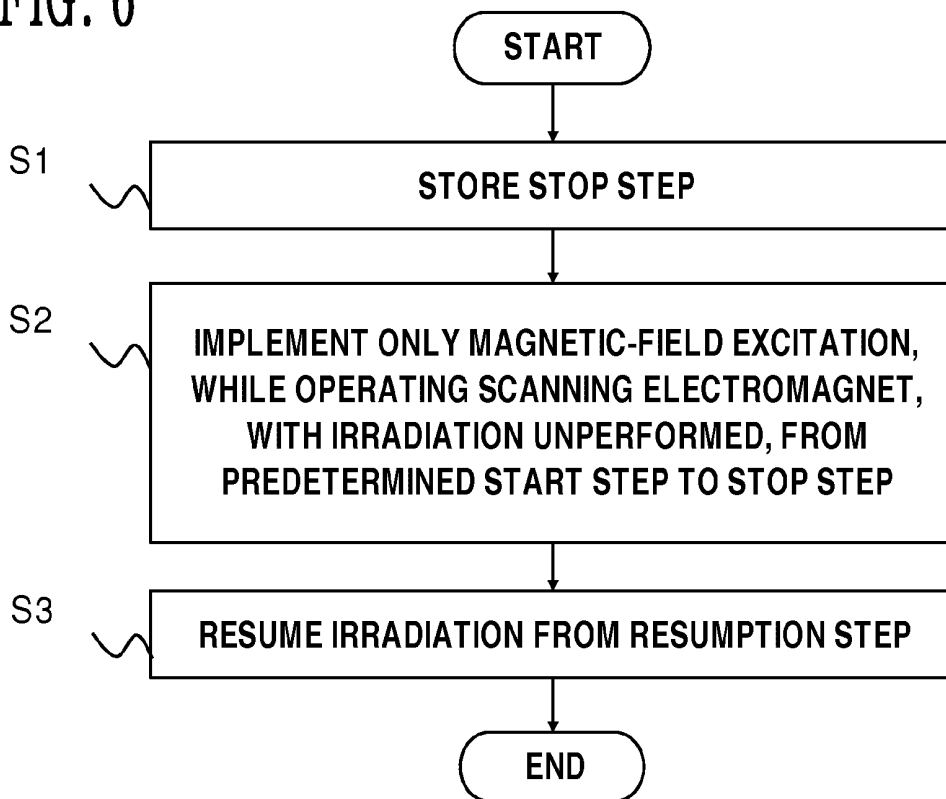


FIG. 7A

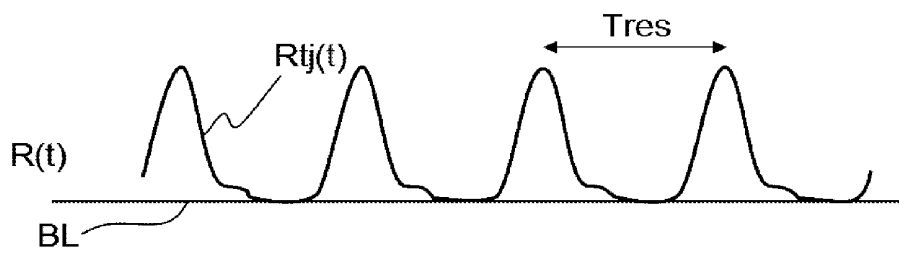


FIG. 7B

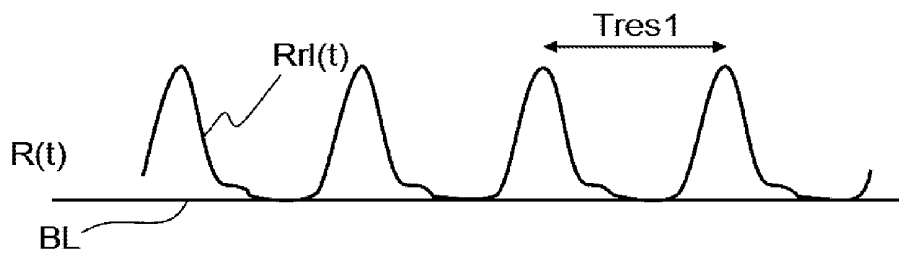


FIG. 8

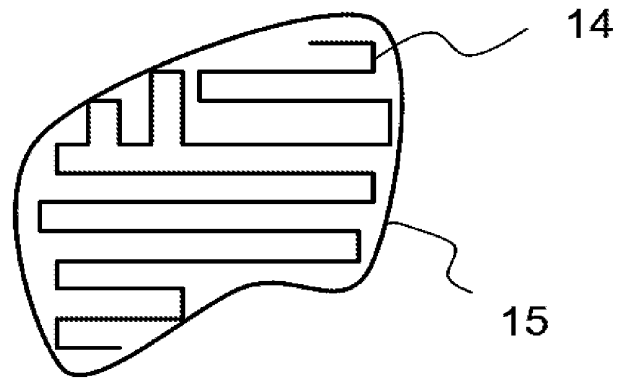


FIG. 9A

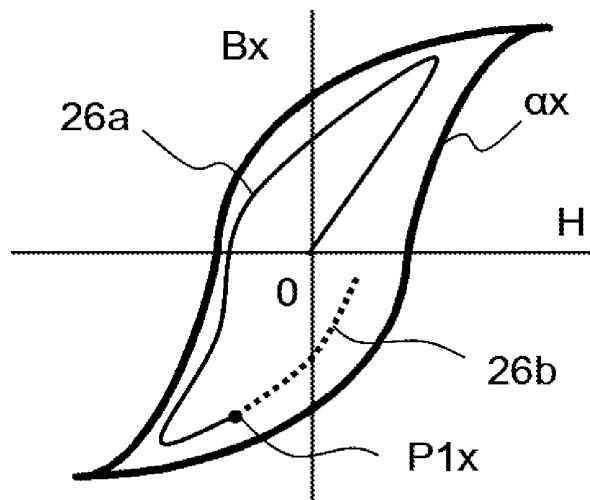
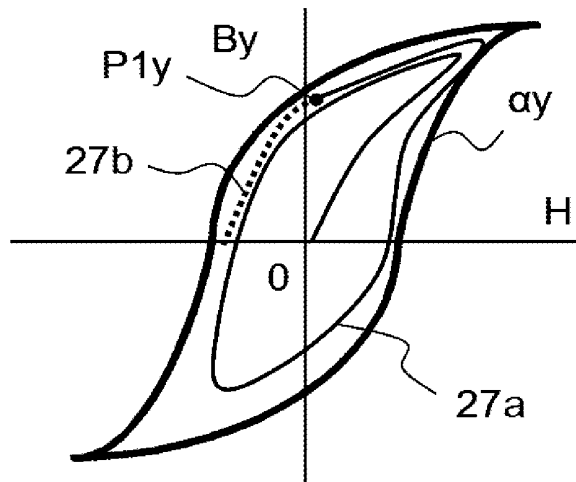
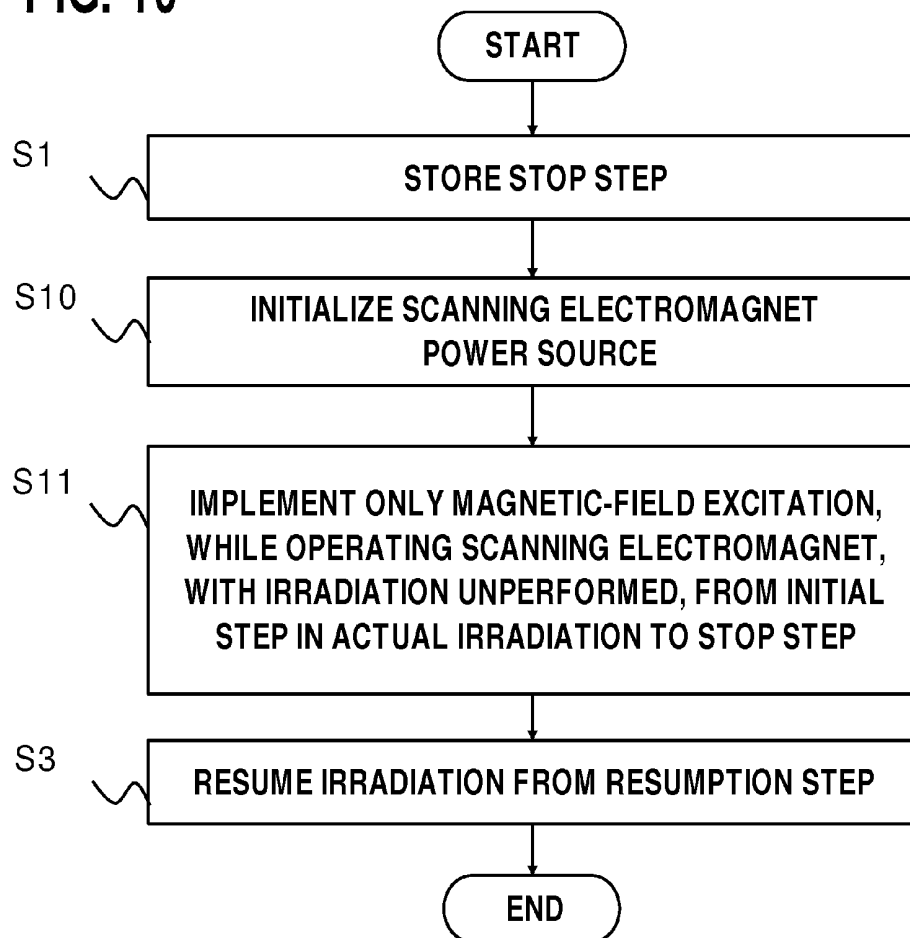


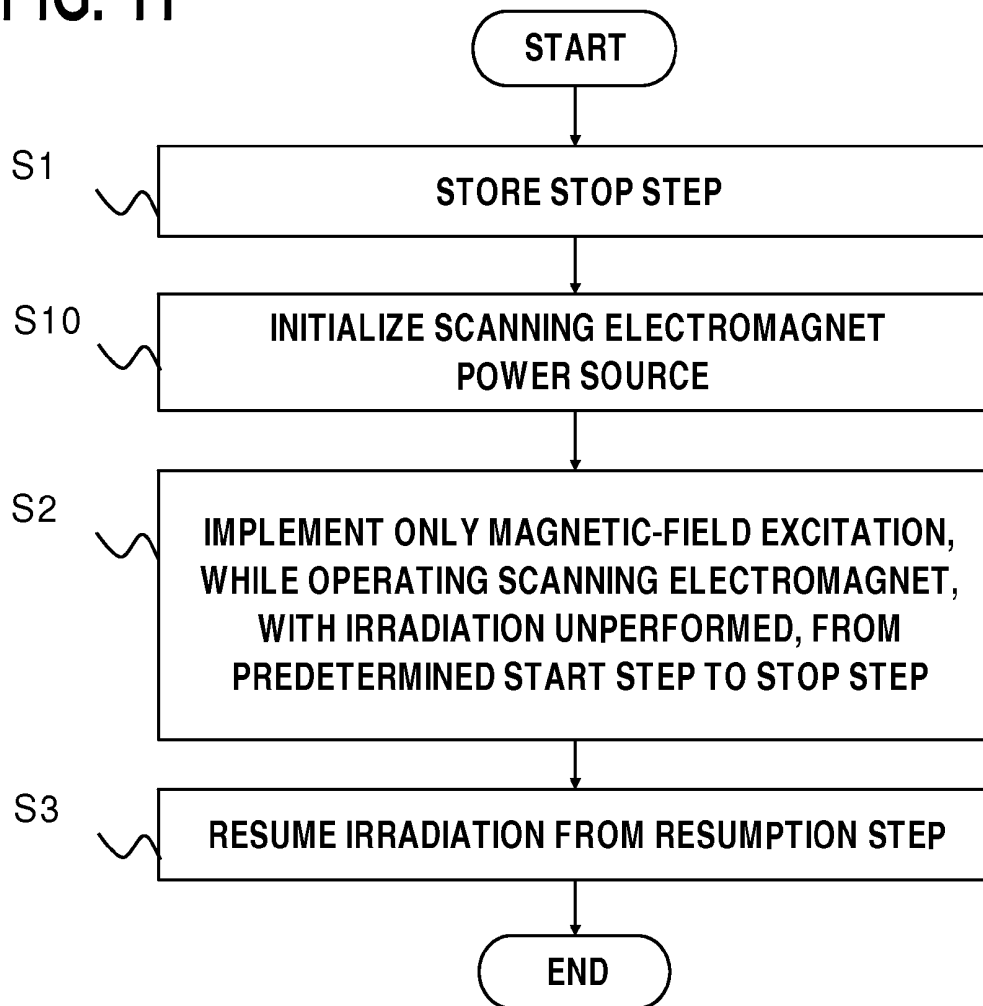
FIG. 9B



**FIG. 10**



**FIG. 11**



## PARTICLE BEAM THERAPY SYSTEM

### TECHNICAL FIELD

[0001] The present invention relates to a particle beam therapy system utilized in the medical field and R&Ds and particularly to a particle beam therapy system of a scanning type such as a spot-scanning type or a raster-scanning type.

### BACKGROUND ART

[0002] In general, a particle beam therapy system is provided with a beam generation apparatus that generates a charged particle beam; an accelerator that is connected with the beam generation apparatus and accelerates a generated charged particle beam; a beam transport system that transports a charged particle beam that is accelerated by the accelerator so as to gain predetermined energy and then emitted; and a particle beam irradiation apparatus, disposed at the downstream side of the beam transport system, for irradiating a charged particle beam onto an irradiation subject, which is a diseased site of a patient or the like. Particle beam irradiation apparatuses are roughly divided into apparatuses utilizing a broad irradiation method in which a charged particle beam is enlarged in a dispersion manner by a scatterer, and the shape of the enlarged charged particle beam is made to coincide with the shape of an irradiation subject in order to form an irradiation field; and apparatuses utilizing a scanning irradiation method (the spot-scanning method, the raster-scanning method, and the like) in which an irradiation field is formed by performing scanning with a thin, pencil-like beam in such a way that the scanning area coincides with the shape of an irradiation subject.

[0003] In the broad irradiation method, an irradiation field that coincides with the shape of a diseased site is formed by use of a collimator or a bolus. The broad irradiation method is a most universally utilized and superior irradiation method where an irradiation field that coincides with the shape of a diseased site is formed so as to prevent unnecessary irradiation onto a normal tissue. However, it is required to create a bolus for each patient or to change the shape of a collimator in accordance with a diseased site.

[0004] In contrast, the scanning irradiation method is a high-flexibility irradiation method where, for example, neither collimator nor bolus is required. However, because these components for preventing irradiation onto not a diseased site but a normal tissue are not utilized, there is required a positional accuracy of beam irradiation that is the same as or higher than that of the broad irradiation method.

[0005] Patent Document 1 discloses the following invention whose objective is to reduce the effect of the hysteresis of a scanning electromagnet for scanning a charged particle beam and to realize high-accuracy beam irradiation. The invention disclosed in Patent Document 1 includes an irradiation management apparatus that controls a scanning electromagnet, based on the desired irradiation position coordinates of a charged particle beam, and a position monitor that measures the measured position coordinates of the charged particle beam.

[0006] The irradiation management apparatus is provided with a command value generator that outputs a control input to the scanning electromagnet, based on the desired irradiation position coordinates and correction data generated on the basis of the measured position coordinates, measured by the position monitor in preliminary irradiation in which the exci-

tation pattern of the scanning electromagnet is the same as that of a actual irradiation plan, and the desired irradiation position coordinates.

[0007] Accordingly, in the invention disclosed in Patent Document 1, the scanning-electromagnet excitation pattern of the preliminary irradiation is the same as that of the planned actual irradiation, and the control input to the scanning electromagnet is preliminarily corrected based on the result obtained in the preliminary irradiation; therefore, the effect of the hysteresis of the scanning electromagnet is eliminated, so that high-accuracy beam irradiation can be realized.

### PRIOR ART REFERENCE

#### Patent Document

[0008] [Patent Document 1] Japanese Patent No. 4532606 (FIGS. 1 and 2)

### DISCLOSURE OF THE INVENTION

#### Problems to be Solved by the Invention

[0009] In the invention disclosed in Patent Document 1, correction is preliminarily performed based on the preliminary irradiation, the scanning-electromagnet excitation pattern for which is the same as that for actual irradiation; therefore, there is demonstrated an extra effect that high-accuracy beam irradiation is realized in the actual irradiation. It is true that when therapy is implemented normally, the invention disclosed in Patent Document 1 poses no problem. However, in a therapy scene, due to a contingency where the size of a charged particle beam exceeds the tolerance range or a patient gets sick, there may occur a situation in which irradiation needs to be interrupted, i.e., emergency-stop processing for the particle beam therapy system needs to be implemented.

[0010] In this case, emergency-stop processing is implemented so as to temporarily stop irradiation of a charged particle beam. Because the diseased site has partly been irradiated with a charged particle beam, it is required that the irradiation of a charged particle beam is resumed from an irradiation position where it has been interrupted, thereby giving a dose planned through a treatment plan to the whole diseased site. In this situation, provided the irradiation is resumed simply from the irradiation position where it has been interrupted, the irradiation pattern of the scanning electromagnet is resumed from the middle thereof. As a result, because the hysteresis affects the scanning electromagnet, the state of the scanning electromagnet at a time when the irradiation is interrupted differs from the state thereof at a time when the irradiation is not interrupted; thus, there has been a problem that while the state of the scanning electromagnet is left different, the actual irradiation is resumed, a charged particle beam is irradiated onto a position that is different from the position at a time when the irradiation is not interrupted, and hence high-accuracy beam irradiation cannot be performed.

[0011] The present invention has been implemented in order to solve the foregoing problems; the objective thereof is to obtain a particle beam therapy system that eliminates the effect of the hysteresis of a scanning electromagnet and can resume high-accuracy beam irradiation from an irradiation position where it has been interrupted.

## Means for Solving the Problems

[0012] There are provided an irradiation management apparatus that controls a scanning electromagnet, based on desired irradiation position coordinates of a charged particle beam; and an interlock information inputting device that generates an interlock signal for stopping irradiation of the charged particle beam, when a contingency occurs. The irradiation management apparatus is provided with a command value generator that outputs a control input to the scanning electromagnet; and a stop step storage memory that stores a stop step corresponding to the desired irradiation position coordinates at which irradiation of the charged particle beam stops, when the interlock signal is generated by the interlock information inputting device. When irradiation of the charged particle beam is resumed, the irradiation management apparatus performs idle operation in which the scanning electromagnet is controlled, with the charged particle beam unirradiated, from a start step, which is situated prior to the stop step and is different from the initial step corresponding to the initial desired irradiation position coordinates in actual irradiation, to the stop step, and then irradiates the charged particle beam from the desired irradiation position coordinates corresponding to the stop step.

## ADVANTAGE OF THE INVENTION

[0013] In the case where emergency-stop processing is performed during therapy, a particle beam therapy system according to the present invention carries out idle operation, based on irradiation command data including a control input to the scanning electromagnet, from a start step, which is situated prior to the stop step and is different from the initial step, and starts beam irradiation from an irradiation position where the irradiation has been interrupted; therefore, the effect of the hysteresis of the scanning electromagnet is eliminated, so that high-accuracy beam irradiation can be resumed from the irradiation position where the irradiation has been interrupted.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. 1 is a configuration diagram illustrating a particle beam therapy system according to Embodiment 1 of the present invention;

[0015] FIG. 2 is a schematic configuration diagram of an accelerator in FIG. 1;

[0016] FIG. 3 is a schematic configuration diagram of a particle beam irradiation apparatus in FIG. 1;

[0017] FIG. 4 is a control block diagram illustrating a particle beam therapy system according to Embodiment 1 of the present invention;

[0018] FIG. 5 is a graph for explaining a method of correcting a command current;

[0019] FIG. 6 is a flowchart representing a procedure for stopping and resuming beam irradiation in a particle beam therapy system according to Embodiment 1 of the present invention;

[0020] FIG. 7A is a chart representing a reference respiratory signal;

[0021] FIG. 7B is a chart representing a real respiratory signal;

[0022] FIG. 8 is a schematic diagram representing a fact that a diseases site is scanned with a beam along a beam path in a particle beam therapy system according to Embodiment 2 of the present invention;

[0023] FIG. 9A and FIG. 9B are charts representing the hysteresis characteristics of a scanning electromagnet in a particle beam therapy system according to Embodiment 2 of the present invention;

[0024] FIG. 10 is a flowchart representing a procedure for stopping and resuming beam irradiation in a particle beam therapy system according to Embodiment 2 of the present invention; and

[0025] FIG. 11 is a flowchart representing another procedure for stopping and resuming beam irradiation in a particle beam therapy system according to Embodiment 2 of the present invention.

## BEST MODE FOR CARRYING OUT THE INVENTION

## Embodiment 1

[0026] The configuration of a particle beam therapy system according to Embodiment 1 of the present invention will be explained below. FIG. 1 is a configuration diagram illustrating a particle beam therapy system according to Embodiment 1 of the present invention. FIG. 2 is a schematic configuration diagram of an accelerator; FIG. 3 is a schematic configuration diagram of a particle beam irradiation apparatus. FIG. 4 is a control block diagram illustrating a particle beam therapy system according to Embodiment 1 of the present invention.

[0027] At first, the outline of the configuration of a particle beam therapy system will be schematically explained with reference to FIG. 1. A particle beam therapy system 51 includes a beam generation apparatus 52, a beam transport system 59, and particle beam irradiation apparatuses 58a and 58b. The beam generation apparatus 52 includes an ion source (unillustrated), a prestage accelerator 53, and a circular accelerator (simply referred to as an accelerator, hereinafter) 54, which is a synchrotron. The particle beam irradiation apparatus 58b is provided in a rotating gantry (unillustrated). The particle beam irradiation apparatus 58a is provided in a treatment room where no rotating gantry is installed. The function of the beam transport system 59 is to achieve communication between the accelerator 54 and the particle beam irradiation apparatuses 58a and 58b. Part of the beam transport system 59 is provided in the rotating gantry (unillustrated), and that part includes a plurality of deflection electromagnets 55a, 55b, and 55c. The beam generation apparatus 52, the beam transport system 59, and the particle beam irradiation apparatuses 58a and 58b are controlled by a control system in a collaborative manner.

[0028] A charged particle beam 1, which is a particle beam such as a proton beam generated in ion source or a carbon beam (heavy particle beam), is accelerated by the prestage accelerator 53 and enters the accelerator 54. The particle beam 1 is accelerated to obtain predetermined energy. The charged particle beam 1 is accelerated by the accelerator 54 in a high-frequency electric field up to 70% to 80% of the light velocity, as it is being bent by means of the magnets. The charged particle beam 1 launched from the accelerator 54 is transported to the particle beam irradiation apparatuses 58a and 58b by way of the beam transport system 59. In the beam transport system 59, the charged particle beam 1 that has received sufficient energy is guided through a path created with a vacuum duct to the particle beam irradiation apparatuses 58a and 58b in respective designated treatment rooms, while its orbit is changed by the electromagnets, as may be necessary. The particle beam irradiation apparatuses 58a and

**58b** each form an irradiation field in accordance with the size and the depth of the diseased site of a patient **24** as an irradiation subject **15**, and each irradiate the charged particle beam **1** onto the irradiation subject **15** (refer to FIG. 3).

[0029] Meanwhile, in the foregoing sentence, the phrase “respective designated treatment rooms” has been described; in general, in view of the therapy efficiency, a particle beam therapy system has a plurality of treatment rooms. That is to say, it is required to provide particle beam irradiation apparatuses **58** as many as the number of treatment rooms. In many cases, a large-size complex system configured with a plurality of subsystems, in general, includes a sub-controller that is dedicated to control of each subsystem and a main controller that conducts and controls the whole system. The particle beam therapy system **51** according to Embodiment 1 of the present invention will be explained based also on a case where this configuration with a main controller and a sub-controller is adopted. For the sake of simplicity, the beam generation apparatus **52** and the beam transport system **59** will be herein referred to as an accelerator system **60**. The system consisting of the particle beam irradiation apparatus **58** and the rotating gantry will be referred to as an “irradiation system”. FIG. 1 illustrates a case where there exist two treatment rooms, i.e., a horizontal irradiation room and a gantry irradiation room. The foregoing controller that controls the accelerator system and the irradiation system in a collaborative manner is a control system of the particle beam therapy system.

#### <Accelerator>

[0030] The accelerator **54** will be explained with reference to FIG. 2. The accelerator **54** is provided with a vacuum duct **61** that serves as an orbit path through which the charged particle beam **1** circulates; an injector **62** for injecting the charged particle beam **1**, supplied from a prestage accelerator **53**, into the vacuum duct **61**; deflection electromagnets **63a**, **63b**, **63c**, and **63d** for deflecting the orbits of charged particles so that the charged particles form the charged particle beam **1** that circulates along a circulation orbit in the vacuum duct **61**; convergence electromagnets **64a**, **64b**, **64c**, and **64d** for converging the charged particle beam **1** formed on the circulation orbit not to diverge; a high-frequency wave acceleration cavity **65** that applies a high-frequency voltage, synchronized with circulating charged particles, to the circulating charged particles so as to accelerate the charged particles; an emission apparatus **66** for extracting from the accelerator **54** the charged particle beam **1** accelerated in the accelerator **54** and emitting the extracted charged particle beam **1** into the beam transport system **59**; and a six-pole electromagnet **67** that excites resonance in the circulation orbit of the charged particle beam **1** in order to make the emission apparatus **66** emit the charged particle beam **1**.

[0031] There are provided unillustrated apparatuses for controlling the respective units; for example, in the deflection electromagnets **63a**, **63b**, **63c**, and **63d**, there are provided deflection electromagnet control apparatuses that control the excitation currents for the deflection electromagnets **63a**, **63b**, **63c**, and **63d**, respectively, and in the high-frequency wave acceleration cavity **65**, there are provided a high-frequency wave source for supplying a high-frequency voltage to the high-frequency wave acceleration cavity **65** and a high-frequency wave control apparatus for controlling the high-frequency wave source; in the control system, there is provided an accelerator control apparatus that controls the whole accelerator by controlling other components such as the

deflection electromagnet control apparatus, the high-frequency wave control apparatus, and the convergence electromagnet **64a**, **64b**, **64c**, and **64d**. However, in the technical idea of the present invention, the control of the accelerator itself is not limited; therefore, the accelerator is not limited to the one having the foregoing configuration, and it goes without saying that various modifications are allowed, as long as the variants can stably emit the charged particle beam **1** into the beam transport system **59**.

#### <Beam Transport System>

[0032] The charged particle beam **1** accelerated by the accelerator **54** is emitted to the beam transport system **59**, which is referred to as an HEBT (High Energy Beam Transport) system. The beam transport system **59** is provided with a vacuum duct that serves as an orbit path of the charged particle beam **1**; a switching electromagnet **68**, which is a switching device for switching the orbits of the charged particle beam **1**; and a deflection electromagnet that deflects a beam at a predetermined angle. The charged particle beam **1** that has been sufficiently energized by the accelerator **54** and travels through the transport path formed of the vacuum duct is led to the irradiation apparatus provided in a designated treatment room; the orbit of the charged particle beam **1** is changed by the switching electromagnet **68**, as may be necessary.

#### <Irradiation System>

[0033] The irradiation system includes the particle beam irradiation apparatus **58** that forms the charged particle beam **1** supplied from the beam transport system **59** into an irradiation field conforming to the size or the depth of a diseased site of a patient as the irradiation subject **15** and that irradiates the charged particle beam **1** onto the diseased site. In general, in the particle beam therapy system **51**, as irradiation field forming methods, the scatterer method, the Wobbler method, and the scanning method have been proposed. The irradiation systems (particle beam irradiation apparatuses) have different configurations, depending on the irradiation methods thereof. The present invention is to be applied to a particle beam therapy system (referred to also as a “scanning-type particle beam therapy system”) utilizing the scanning method typified by spot scanning or raster scanning. When being a scanning-type particle beam therapy system, the particle beam irradiation apparatus **58** is provided with a pair of scanning electromagnets **3** for scanning the pencil-shaped charged particle beam **1** in accordance with the shape of the irradiation subject **15** and a position monitor **7** for measuring an irradiation position and the like. The detailed configuration of the particle beam irradiation apparatus **58** will be described later.

#### <Control System>

[0034] The control system will be explained with reference to FIG. 4, which illustrates the functional block. Meanwhile, in general, as the controller of the particle beam therapy system **51**, a workstation or a computer is utilized. Accordingly, in many cases, the controller is referred to as a “computer”. For example, the main controller **70** in FIG. 4 is, in fact, a function of a computer, which is, in many cases, referred to as an irradiation system common computer; however, the main controller **70** is dealt with as a controller having a specific function. Each of the sub-controllers **71a** and **71b** is a function of a computer, which is, in many cases, referred to

as an apparatus control computer; however, each of the sub-controllers **71a** and **71b** is dealt with as a controller having a specific function. The sub-controllers **71a** and **71b** perform control of the whole subsystems, which consists of a part of apparatuses in the treatment room, such as a treatment table for laying a patient **24** and an X-ray image-capturing device for radiographing the position of a diseased site (irradiation subject **15**).

[0035] An irradiation system **80** is configured with the main controller **70**, apparatuses provided in an irradiation operation room **81**, apparatuses provided in a treatment room **82a**, and apparatuses provided in a treatment room **82b**. In the treatment room **82a**, there is arranged an irradiation apparatus unit **31a** of the particle beam irradiation apparatus **58a**. In the treatment room **82b**, there is arranged an irradiation apparatus unit **31b** of the particle beam irradiation apparatus **58b**.

[0036] The “consoles” **72a**, **72b**, **73a**, **73b**, **74a**, and **74b** connected with the sub-controllers **71a** and **71b** are each a keyboard, a display, or the like or a terminal such as a controller box; in other words, they are each a man-machine interface. The consoles **72a** and **72b** are provided in the irradiation operation room **81**; the consoles **73a** and **74a** are provided in the treatment room A (**82a**); the consoles **73b** and **74b** are provided in the treatment room B (**82b**). Control boards **75a** and **75b** are connected with the bottom parts of the sub-controllers **71a** and **71b**, respectively. Each of the control boards **75a** and **75b** includes, specifically, a driver, an amplifier, a sequencer, and the like for various kinds of apparatuses **76a**, **76b**, **77a**, and **77b**, which are control subjects. The control board **75a** allows communication of signals between the main controller **70** and an interlock information inputting device **84a** and between the main controller **70** and the irradiation apparatus unit **31a**; the control board **75b** allows communication of signals between the main controller **70** and an interlock information inputting device **84b** and between the main controller **70** and the irradiation apparatus unit **31b**. The apparatuses **76a** and **77a**, the interlock information inputting device **84a**, and the irradiation apparatus unit **31a** are connected with the bottom part of the sub-controllers **71a** by way of the control board **75a**; the apparatuses **76b** and **77b**, the interlock information inputting device **84b**, and the irradiation apparatus unit **31b** are connected with the bottom part of the sub-controllers **71b** by way of the control board **75b**. Each of the apparatuses **76a**, **76b**, **77a**, and **77b** is, specifically, a motor for moving the respective axles of a treatment table, a motor for driving an X-ray image-capturing device in the irradiation apparatus, or the like. A scanning electromagnet power source **4** supplies respective energization currents to scanning electromagnets **3a** and **3b** provided in the irradiation apparatus units **31a** and **31b**, respectively, by way of a switching circuit **79**.

[0037] The motor for the treatment table and the motor for the X-ray image-capturing device are not moved when a beam is being irradiated. That is to say, it is not required to implement control in synchronization with the electromagnet for the accelerator and the like controlled by the accelerator system **60**. In order to exchange information about their conditions, the main controller **70** and the sub-controller **71a** or **71b** communicate with each other, for example, by use of a Ready signal that indicates in which treatment room the irradiation apparatus unit **31a** or **31b** has completed its positioning and is ready to irradiate a beam, and a signal that indicates in which treatment room the irradiation apparatus unit **31a** or

**31b** has irradiated a beam and completed its irradiation, and the like. Briefly speaking, it is regarded as carrying out events sequentially.

[0038] Here, the functions of the irradiation system common computer (main controller **70**) and the apparatus control computers (sub-controllers **71a** and **71b**) will be explained. As described above, in the treatment rooms **82a** and **82b**, there are provided the irradiation apparatus units **31a** and **31b** of the particle beam irradiation apparatuses **58a** and **58b**, respectively. Additionally, as described above, in the case of a scanning-type particle beam therapy system, in each of the irradiation apparatus units **31a** and **31b**, there are provided a pair of scanning electromagnets **3**, the position monitor **7** for measuring an irradiation position, and the like. In this regard, however, as illustrated in FIG. **4**, control of the scanning electromagnets **3** and processing of signals from the position monitor **7** are performed not by the apparatus control computer but by the irradiation system common computer (an irradiation management apparatus, described later).

[0039] The foregoing fact is based on two reasons. The first reason is requirement for control in synchronization with the accelerator system; the second reason is instantaneousness (requirement for reducing wasteful time as much as possible). In order to realize irradiation as per a treatment plan, it is required to control the accelerator system **60** and the irradiation system **80** in such a way that they are synchronized with each other. It is true that the sub-controllers **71a** and **71b** and the main controller **70** can perform processing at the same time and in a parallel manner, by use of a synchronization signal or the like. However, the more apparatuses to be passed through there are, the more wasteful time occurs and hence control performance is deteriorated. Accordingly, in the particle beam therapy system **51** according to the present invention, the accelerator system **60**, the scanning electromagnet **3**, and the like, which need to be controlled in real time during irradiation of a beam, are controlled by the irradiation system common computer (the irradiation management apparatus), which is the main controller **70**; in contrast, the treatment table, the X-ray image-capturing device, and the like, which do not need to be driven during irradiation of a beam, are controlled by the apparatus control computers, which are the sub-controllers **71a** and **71b**.

[0040] This is because intensive management by a single main controller **70** can reduce wasteful time as much as possible, thereby realizing high-accuracy beam irradiation without deteriorating the control performance. For the purpose of ensuring the instantaneousness, as well, it is desirable that signal processing for the interlock information inputting devices **84a** and **84b** and the like, which function as the interlock (emergency-stop processing), and the like are performed by the irradiation system common computer (the irradiation management apparatus), which is the main controller **70**. The irradiation system common computer is provided with a so-called “contest for accelerator” function in which it is managed which treatment room occupies the charged particle beam **1**.

[0041] Next, the particle beam irradiation apparatus **58** will be explained with reference to FIG. **3**. The particle beam irradiation apparatus **58** is provided with the irradiation apparatus unit **31**, the scanning electromagnet power source **4**, the interlock information inputting device **84**, and an irradiation management apparatus **32** that performs control of the irradiation apparatus unit **31** and the interlock information inputting device **84**, collection of data, and the like. The interlock

information inputting device **84** is provided with a patient sensor **78**, described later. The irradiation apparatus unit **31** is provided with a beam transport duct **2** for transporting the charged particle beam **1** injected by the beam transport system **59**; scanning electromagnets **3x** and **3y** that scan the charged particle beam **1** in the X direction and the Y direction, respectively, which are directions perpendicular to the charged particle beam **1**; a position monitor **7**; a preamplifier **9** that amplifies a signal from the position monitor **7**; a position monitor unit **8**; a dose monitor **11**; a preamplifier **13** that amplifies a signal from the dose monitor **11**; a dose monitor unit **12**; a beam enlargement apparatus **16**; a beam enlargement control apparatus **17**; a bellows **18**; a vacuum duct **19**; a ripple filter **20**; a range shifter **21**; and a range shifter unit **23**. As illustrated in FIG. 3, the incident direction of the charged particle beam **1** is the Z direction.

**[0042]** The scanning electromagnet **3x** is an X-direction scanning electromagnet that scans the charged particle beam **1** in the X direction; the scanning electromagnet **3y** is a Y-direction scanning electromagnet that scans the charged particle beam **1** in the Y direction. The position monitor **7** detects the size of the charged particle beam **1**, which has been deflected by the scanning electromagnets **3x** and **3y**, and the passing position (the gravity center position) through which the charged particle beam **1** passes. The preamplifier **9** amplifies analogue data on the passing position and the beam size detected by the position monitor **7**. Here, the beam size denotes an area, in the XY plane perpendicular to the Z direction, through which the charged particle beam **1** passes. The position monitor unit **8** receives the passing position and the beam size detected by the position monitor **7**, through the preamplifier **9**; then, the position monitor unit **8** converts the passing position and the beam size into digital data so as to create measured position coordinates **Ps** and a measured beam size **Ss**.

**[0043]** The dose monitor **11** detects the dose of the charged particle beam **1**. The preamplifier **13** amplifies analogue data on the dose detected by the dose monitor **11**. The dose monitor unit **12** receives the dose detected by the dose monitor **11**, through the preamplifier **13**; then, the dose monitor unit **12** converts the dose into digital data so as to create a measured dose **Ds**.

**[0044]** The beam enlargement apparatus **16** enlarges the beam size of the charged particle beam **1**, as may be necessary. The vacuum duct **19** ensures a vacuum region through which the charged particle beam **1** passes. The bellows **18** connects the beam transport duct **2** with the vacuum duct **19** in an expandable/contractible manner and extends the vacuum region toward the irradiation subject **15**. The ripple filter **20** is also referred to as a ridge filter and formed in a convex shape. The ripple filter **20** causes an energy loss to the charged particle beam **1**, which is a monochromatic beam having approximately single energy and transported from the accelerator **54**, so that the energy has a range.

**[0045]** The depth-direction (Z direction) position coordinates of the irradiation subject **15** is controlled by varying the energy of the charged particle beam **1** through change in the acceleration energy of the accelerator **54** and by varying the energy of the charged particle beam **1** through the range shifter **21**. The range shifter **21** adjusts the range of the charged particle beam **1** little by little. Considerable change of the range of the charged particle beam **1** is performed by changing the acceleration energy of the accelerator **54**, and

slight change of the range of the charged particle beam **1** is performed by changing the setting of the range shifter **21**.

**[0046]** The irradiation management apparatus **32** reads the treatment plan data pieces **F0** generated by the treatment planning apparatus; then, in order to control the irradiation dose, the irradiation management apparatus **32** creates setting data **Fi** by rearranging the treatment plan data pieces in order of irradiation onto irradiation spots, which are divided irradiation units. In other words, the setting data **Fi** is sequentialized treatment plan data (sequential data, described later). Based on the setting data **Fi**, the irradiation management apparatus **32** outputs the setting data pieces **Fo**, which are respective commands to the apparatuses.

**[0047]** The elements of the setting data **Fi** are desired irradiation position coordinates **Pi**, a desired dose **Di**, a desired beam size **Si**, a desired accelerator setting **Bi**, and a range shifter insertion amount **Ri**; respective elements of the setting data **Fi** are data items obtained by sequentializing a desired irradiation position coordinates **Pi0**, a desired dose **Di0**, a desired beam size **Sio**, a desired accelerator setting **Bi0**, and a range shifter insertion amount **Ri0**, which are the elements of the treatment plan data **F0**. The setting data **Fo** includes an accelerator setting command **Bo**, a range shifter command **Ro**, a command current **Io** (an uncorrected command current), a command current **Ir** (a command current obtained by correcting the command current **Io**), a beam size command **So**, and a desired dose **Do**.

**[0048]** The irradiation management apparatus **32** receives irradiation records such as the measured position coordinates **Ps**, the measured dose **Ds**, and the measured beam size **Ss** in preliminary irradiation performed when the patient **24** does not exist, and evaluates the irradiation records. The irradiation management apparatus **32** creates the command current **Ir** by correcting the command current **Io**, based on the measured position coordinates **Ps**, and transmits the command current **Io** or the command current **Ir** to the scanning electromagnet power source **4**. The irradiation management apparatus **32** receives irradiation records, such as the measured position coordinates **Ps**, the measured dose **Ds**, and the measured beam size **Ss** in actual irradiation where irradiation onto the patient **24** is actually performed, and stores the irradiation records in the actual irradiation in the patient file server.

**[0049]** The irradiation management apparatus **32** outputs a trigger signal, a count start signal, a beam supply command, and a beam stop command, and controls the irradiation spot and the irradiation dose at the irradiation subject **15**. The irradiation spots are layers divided in the Z direction; each irradiation spot is divided into a slice, which corresponds to the kinetic energy of the charged particle beam **1**, and the XY direction at each slice. In this embodiment, there will be explained an irradiation method in which the charged particle beam **1** is stopped when slices are changed, and the charged particle beam **1** is continuously irradiated when irradiation is performed within a single and the same slice. The irradiation management apparatus **32** scans the charged particle beam **1** onto respective slices, of the irradiation subject **15**, that are layers corresponding to kinetic energy levels. The irradiation management apparatus **32** changes setting of each apparatus for each irradiation spot in response to the trigger signal, and starts to measure the irradiation dose of an irradiation spot in response to the count start signal; when the measured dose **Ds** reaches the desired dose **Do**, the irradiation management apparatus **32** performs control for the next irradiation spot; when respective irradiations onto irradiation divisions

(slices) obtained by dividing the irradiation subject **15** are completed, the irradiation management apparatus **32** outputs the beam stop command to the accelerator system **60** so as to stop the charged particle beam **1**. Next, the irradiation management apparatus **32** outputs the trigger signal and sequentially changes the corrected command current  $I_r$ , the beam size command  $S_o$ , the accelerator setting command  $B_o$ , and the range shifter command  $R_o$ ; then, the irradiation management apparatus **32** performs irradiation of the charged particle beam **1** until irradiation onto all the slices of the irradiation subject **15** is completed.

**[0050]** The scanning electromagnet power source **4** changes the setting currents for the scanning electromagnets  $3_x$  and  $3_y$ , based on the command current  $I_o$  ( $I_r$ ), which is outputted from the irradiation management apparatus **32** and is a control input to the scanning electromagnet **3**. The beam enlargement control apparatus **17** outputs to the beam enlargement apparatus **16** the beam size command  $S_o$  for setting the beam size at the position monitor **7**. The range shifter unit **23** outputs to the range shifter **21** the range shifter command  $R_o$  for changing the energy of the charged particle beam **1**.

**[0051]** The patient sensor **78** detects the motion of the patient **24** and outputs a patient signal on which the motion of the patient **24** is reflected. The patient sensor **78** is to stop irradiation when the motion of the patient exceeds a predetermined range, i.e., to perform emergency-stop processing for the particle beam therapy system. As the patient sensor **78**, the following devices may be utilized. Specifically, there are conceivable a method of detecting the flow of expired air by means of a flow sensor, a method of measuring the temperature change, due to inspiration, in the vicinity of nasal cavities through image processing by a thermistor or an infra-red camera, a method of detecting the abdominal movement of a patient by means of a position sensitive detector (position sensor) that senses a laser-beam source mounted on the abdomen, and a method of converting the abdominal movement of a patient into a signal by means of a laser displacement gauge. Additionally, the patient sensor **78** may be utilized also as the respiratory sensor that is utilized for respiration-synchronized irradiation of the particle beam therapy system **51**. This is because both the respiratory sensor and the patient sensor are utilized for the purpose of detecting the motion of the patient **24**.

**[0052]** Next, the technology disclosed in Patent Document 1, which is a basis of the present invention, will briefly be explained. The invention disclosed in Patent Document 1 has been implemented for the particle beam therapy system **51** that irradiates the charged particle beam **1**, accelerated by the accelerator **54** and scanned by the scanning electromagnet **3**, onto the irradiation subject **15**; the particle beam therapy system has the following characteristics:

**[0053]** (A) There is provided the irradiation management apparatus **32** that controls the scanning electromagnet **3**, based on the desired irradiation position coordinates  $P_i$  of the charged particle beam **1**;

**[0054]** (B) There is provided a position monitor **7** that measures the measured position coordinates  $P_s$  of the charged particle beam **1**; and

**[0055]** (C) The irradiation management apparatus **32** is provided with a command value generator that outputs the control input  $I_o$  ( $I_r$ ) to the scanning electromagnet **3**, based on the desired irradiation position coordinates  $P_i$  and the correction data  $l_a$  generated on the basis of the measured position

coordinates  $P_s$ , measured by the position monitor **7** in the preliminary irradiation in which the excitation pattern of the scanning electromagnet **3** is the same as that of the actual irradiation plan, and the desired irradiation position coordinates  $P_i$ .

**[0056]** The method of creating the current correction data  $l_a$  will be explained. FIG. 5 is a graph for explaining a method of correcting a command current. There is measured the BL product vs. the current  $I$ , which is outputted to the scanning electromagnet **3** in response to the command current  $I_o$  applied to the scanning electromagnet power source **4**. The BL product is multiplication product of the intensity  $B$  of the magnetic field and the effective length  $L$  of the magnetic pole of the scanning electromagnet **3**. There is drawn a maximum hysteresis curve  $\alpha$  that passed through the saturated magnetic flux density. By averaging the one portion of the maximum hysteresis curve  $\alpha$ , which is drawn in such a way that the current increase, and the other portion of the maximum hysteresis curve  $\alpha$ , which is drawn in such a way that the current decreases, the center line  $\beta$  of the hysteresis loop is obtained.

**[0057]** The current value  $I(id)$  set through the command current  $I_o$  is determined by the desired irradiation position coordinates  $P_i$ , at which irradiation is performed, the center line  $\beta$  of the hysteresis loop, the energy of the charged particle beam **1**, and the distance between the position at which the scanning electromagnet **3** is disposed and the irradiation position. While considering the Lorentz force exerted on the charged particle beam **1**, the value of the BL product can be obtained from the position coordinates of the charged particle beam **1**. The command current  $I_o$  is a command value that corresponds to the current  $I(id)$  at the intersection point  $P'$  (not represented) of the value  $BL(id)$  of the ideal BL product calculated from the desired irradiation position coordinates  $P_i$  with the center line  $\beta$  of the hysteresis loop.  $BL(id)$  is the expected value  $BL(ex)$  of the value of the BL product to be measured.

**[0058]** A value  $BL(me)$  of the BL product is calculated from the measured position coordinates  $P_s$ . The point  $P$  in FIG. 5 is the actually measured value. There will be considered a case where the value  $BL(me)$  of the measured BL product is displaced by  $ABL$  from the expected value  $BL(ex)$ . In order to correct the current, the displacement by  $ABL$  is made by use of a straight line having a gradient  $K$ , which is a tangential line at the intersection point  $P'$  at which the command current  $I_o$  is obtained. In order to make a correction, there is obtained the current value  $I1$  at which the BL product becomes  $BL(ex)$ . After the current value  $I1$  is obtained, there can be generated the command current  $I_r$  for setting the current value to the current value  $I1$  corresponding to  $BL(id)$ . In such a way as described above, the displacement of the charged particle beam **1** due to the hysteresis of the scanning electromagnet **3** can be made to fall within a tolerance range.

**[0059]** The straight line (dashed line)  $\gamma$  is a line having the gradient  $K$  that is the same as the gradient of the tangential line, at the current value  $I(id)$ , of the center line  $\beta$ . The gradient  $K$  can be expressed by the equation (1), and the corrected current value  $I1$  can be expressed by the equation (2).

$$K = \frac{dBL}{dI}(id) \quad (1)$$

-continued

$$I1 = I(id) - \frac{\Delta BL}{K} \quad (2)$$

where  $\Delta BL = BL(me) - BL(ex)$ . The correction current value  $\Delta I$  to be set through the current correction data Ia is  $\Delta BL/K$ .

[0060] Next, there will be considered a case where emergency-stop processing for the particle beam therapy system 51 is performed. As described above, the emergency-stop processing is processing of interrupting irradiation when a contingency occurs. The situation where the emergency-stop processing should be performed is, for example, a case where the measured position coordinates Ps or the measured beam size Ss, of the charged particle beam 1, detected by the position monitor 7 exceeds an allowable value, or a case where there occurs such a contingency as the patient 24 becomes ill, or the like. FIG. 3 illustrates a case where the particle beam irradiation apparatus 58 according to Embodiment 1 is provided with the patient sensor 78 that detects the motion of a patient; however, there are provided therein a patient call button (unillustrated) for the patient 24 to inform that the patient 24 himself or herself has become ill and an irradiation stop button (unillustrated) that enables a doctor or an engineer or the like to stop irradiation in the event of an emergency. Each of the patient sensor 78, the patient call button, the irradiation stop button, and the position monitor 7 works as the interlock information inputting device 84 that generates an interlock signal that activates the interlock function for stopping beam irradiation in the event of an contingency so as to ensure the safety. The interlock information inputting device 84 includes a signal generator that generates the interlock signal from a signal outputted by the patient sensor 78, the patient call button, the irradiation stop button, or the position monitor 7.

[0061] As described above, in the interlock processing (emergency-stop processing), instantaneousness is required; thus, it is desirable that this signal processing is performed by the irradiation system common computer (irradiation management apparatus 32), which is the main controller 70. The irradiation management apparatus 32, which is the main controller 70, according to Embodiment 1 of the present invention has the following characteristics.

[0062] The irradiation management apparatus 32 determines that irradiation should be stopped, when the motion of the patient 24 exceeds a predetermined range, from a signal (the patient signal) detected by the patient sensor 78. The irradiation management apparatus 32 determines that irradiation should be stopped, when the measured position coordinates Ps or the measured beam size Ss of the charged particle beam 1, detected by the position monitor 7, exceeds a predetermined range (an allowable value) (corresponding to a case where the quality of the charged particle beam 1 is deteriorated). The irradiation management apparatus 32 determines that irradiation should be stopped also in the event of an emergency where by operating the patient call button, the patient 24 informs that he has become ill, or an emergency where by operating the irradiation stop button, a doctor or an engineer or the like expresses his or her will to stop irradiation. The irradiation management apparatus 32, which is the main controller 70, controls also the accelerator system 60 (the accelerator 54, the beam transport system 59); therefore, when determining that irradiation should be stopped, the irradiation management apparatus 32 can stop the irradiation

of the charged particle beam 1, by controlling the accelerator system 60. The predetermined range for the motion of the patient 24 detected by the patient sensor 78 is a range obtained by adding a margin to the detection value corresponding to the moving range of the patient 24 at a time when the patient 24 normally respire. There will be described later the method in which the motion of the patient 24 is detected and then it is determined whether or not the motion has exceeded the predetermined range.

[0063] The irradiation management apparatus 32 according to Embodiment 1 is further provided with the following characteristics. As described above, the irradiation management apparatus 32 includes a command value generator that outputs correction data Ia generated based on preliminary irradiation and a control input for the scanning electromagnet 3. That is to say, the irradiation management apparatus 32 includes a control input, as sequential data, preliminarily corrected by the command value generator. The sequential data denotes such data as is implemented step by step (every discrete processing that is implemented in a predetermined time). Because the desired irradiation position coordinates Pi is given as sequential data, there is required, also as sequential data, the control input, for the scanning electromagnet 3, that corresponds to the desired irradiation position coordinates Pi. Base on the interlock signal generated by the interlock information inputting device, the irradiation management apparatus 32 performs the foregoing determination on irradiation stop; when the irradiation is stopped, the irradiation management apparatus 32 stores the step (stop step) corresponding to that desired irradiation position coordinates Pi (i.e., stop position coordinates) in a stop step storage memory, which is incorporated therein. For example, there is stored the number "n" of a step in which there is outputted a control input corresponding to the desired irradiation position coordinates Pi in a given slice (stop step storage procedure). The stop step storage memory may be provided not only in the irradiation management apparatus 32 but also outside the irradiation management apparatus 32.

[0064] The irradiation management apparatus 32 according to Embodiment 1 of the present invention is further provided with the following characteristics. In particle beam therapy, a single therapy time is approximately 30 minutes; out of the 30 minutes, several minutes are for irradiation. It cannot necessarily be said that during the particle beam therapy, there occurs no contingency such as the patient 24 becoming ill, the patient 24 having a coughing fit, or the quality of the charged particle beam 1 being deteriorated. The case where the measured position coordinates Ps or the measured beam size Ss of the charged particle beam 1, detected by the position monitor 7, exceeds a predetermined range (an allowable value) corresponds to a case where the quality of the charged particle beam 1 is deteriorated. In this case, irradiation is stopped through sensing by a sensor or by operating a button or the like so that the therapy is interrupted. In the case where the foregoing contingency is cancelled and irradiation is resumed, the irradiation management apparatus 32 controls the scanning electromagnet 3 with a beam unirradiated, for example, from the initial step for a given slice (idle operation procedure). Control of the scanning electromagnet 3 with a beam unirradiated will be referred to herein as "idle operation". The step where the idle operation is started will be referred to as a start step.

[0065] This is for the following reason. When irradiation is resumed simply from an irradiation position at which the

irradiation has been interrupted, control of the scanning electromagnet **3** is performed halfway through the excitation pattern; however, when the scanning electromagnet **3** is controlled from the initial step for a given slice, the control can be performed with the same excitation pattern as the preliminary irradiation has been performed. It goes without saying that when a beam is irradiated at this timing, double irradiation is caused; thus, it is significant to perform the idle operation. Accordingly, correction based on the preliminary irradiation becomes effective, and high-accuracy beam irradiation can be performed at the same level as when there exists no interruption.

**[0066]** In view of the reproducibility, it is desirable to perform the idle operation from the initial step for a given slice; however, it is empirically known that even when the idle operation is performed from a step that is predetermined steps (predetermined spots) prior to the step corresponding to the stop position, a considerable effect can be obtained. Thus, in Embodiment 1, as the start step, there is selected the initial step for a given slice, or is selected the step that is prior to the step corresponding to the stop position by predetermined steps which are preliminarily set. That is to say, the operator such as a doctor or an engineer can make selection between idle operation to be performed from the initial step for a given slice and idle operation to be performed from a step that is prior to the step corresponding to the stop position by predetermined steps which are preliminarily set.

**[0067]** Here, there will be explained the method of making decision on how many the predetermined steps should be. The effective number of steps for the idle operation depends mainly on the scale or the performance of the scanning electromagnet **3**. Thus, it is desirable that an interrupted situation is actually and intentionally reproduced, experiments are carried out with a different number of steps, and after the confirming the effect, the number of steps is decided. In some cases, the idle operation is performed from halfway through the immediately previous slice. It is allowed that, as described above, the idle operation is performed from a step that is prior to the initial step for a given slice.

**[0068]** Lastly, it is required that the irradiation management apparatus **32** controls the particle beam irradiation apparatus **58** in such a way that there is irradiated the portion onto which a beam has not been irradiated due to interruption. Therefore, the irradiation management apparatus **32** controls the accelerator system **60** (the accelerator **54**, the beam transport system **59**) in such a way that after idle operation is carried out up to a step corresponding to the stop position, beam irradiation is started from the resumption step that follows the stop step, so that the remaining steps can be performed (irradiation start procedure). In the case of an irradiation method in which the charged particle beam **1** is stopped when slices are changed and the charged particle beam **1** is continuously irradiated when irradiation is performed within a single and the same slice, sequential time management (step management) enables the irradiation position and the irradiation dose at the irradiation position to be reproduced. That is to say, even in the case where the irradiation dose at an irradiation spot, which is a stop position where irradiation has been interrupted, has not reached the desired dose  $D_0$ , irradiation is resumed with a halfway irradiation dose, and after the irradiation dose at the irradiation spot reaches the desired dose  $D_0$ , irradiation can move to the next irradiation spot.

**[0069]** The characteristics of the irradiation management apparatus **32** have been explained; the flow of the emergency-

stop processing by the particle beam therapy system **51** will be summarized by use of FIG. 6. FIG. 6 is a flowchart representing a procedure for stopping and resuming beam irradiation in a particle beam therapy system according to Embodiment 1. In the case where during the particle beam therapy, there occurs a contingency such as the patient **24** becoming ill, the patient **24** having a coughing fit, or the quality of the charged particle beam **1** being deteriorated, the irradiation management apparatus **32** performs the foregoing determination on irradiation stop, based on the interlock signal generated by the interlock information inputting device, and stops the irradiation. When the irradiation is stopped, the irradiation management apparatus **32** stores the step corresponding to that desired irradiation position coordinates  $P_i$  (i.e., stop position coordinates). For example, there is stored the number "n" of a step in which there is outputted a control input corresponding to the desired irradiation position coordinates  $P_i$  in a given slice (the step S1: the stop step storage procedure). In the case where the foregoing contingency is cancelled and irradiation is resumed, the irradiation management apparatus **32** activates the scanning electromagnet power source **4**, with a beam unirradiated in the process from a predetermined start step to the stop step, so as to perform only magnetic-field excitation of the scanning electromagnet **3** (the step S2: the idle operation procedure). After the idle operation is carried out up to a step corresponding to the stop position, the irradiation management apparatus **32** controls the accelerator system **60** (the accelerator **54**, the beam transport system **59**) from the resumption step that follows the stop step so as to resume beam irradiation (the step S3, the irradiation start procedure).

**[0070]** As a result, in the particle beam therapy system **51** according to Embodiment 1, even in the case where a contingency such as a patient becoming ill occurs, irradiation can be interrupted by operating a sensor or a button or the like, and the scanning electromagnet **3** is controlled, with a beam unirradiated, from the initial step for a given slice or from a step that is predetermined steps before (start step); thus, the excitation pattern for the scanning electromagnet **3** is made the same as that at a time when preliminary irradiation is performed, correction based on the preliminary irradiation (i.e., information from the preliminary irradiation) can be made effective, and hence high-accuracy beam irradiation can be realized. Accordingly, even in the case where the emergency-stop processing is performed during therapy, the effect of the hysteresis of the scanning electromagnet **3** can be eliminated and high-accuracy beam irradiation can be resumed from an irradiation position where irradiation has been interrupted.

**[0071]** There will be explained the method in which the motion of the patient **24** is detected and then it is determined whether or not the motion has exceeded a predetermined range. A change caused by normal respiration is measured, as a respiratory signal, through the foregoing patient sensor **78** so that there is preliminarily obtained a reference patient status waveform, which is a temporally-changing waveform of a respiratory signal as a reference (reference respiratory signal). A real patient status waveform, generated from a respiratory signal (real respiratory signal) that is measured by the patient sensor **78** during actual irradiation, is compared with a reference patient status waveform, and it is determined whether or not the difference between the real patient status waveform and the reference patient status waveform has exceeded a predetermined range. As the patient sensor **78** for measuring the reference respiratory signal, there is utilized a

patient sensor of a type the same (the same measurement principle) as that of the patient sensor 78 for measuring the respiratory signal during therapy.

**[0072]** Although not a complete trigonometric function, the reference respiratory signal is a signal of an approximately constant cycle; therefore, there is considered a method in which by converting the reference respiratory signal into a trigonometric function that is closest thereto, the gain (the amplitude of the trigonometric function) and the phase are calculated. Fourier series expansion is applied to the reference respiratory signal  $R_{rj}(t)$ , for example, as represented in the equation (3); as represented in the equation (4), among the expanded 0th-order term through nth-order term, a pair of coefficients  $a_1$  and  $b_1$ , of the trigonometric function, which correspond to the 1st-order term of the equation (3) are calculated; then, the calculated coefficients  $a_1$  and  $b_1$  are specified as the describing functions that indicate the state of the respiratory signal. In other words, there are calculated the coefficients  $a_1$  and  $b_1$  of the cosine function and the sine function that configure the fundamental waveform component that is obtained by removing the constant term and the high-frequency components from the reference respiratory signal. FIG. 7A represents the waveform of a describing function formed of  $a_1$  and  $b_1$  obtained from the reference respiratory signal NW and the equation (2).

$$R(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos(n\omega_{res}t) + b_n \sin(n\omega_{res}t)) \quad (3)$$

$$\left. \begin{aligned} a_1 &= \frac{1}{\pi} \int_0^{2\pi} R(t) \cos(\omega_{res}t) d\omega_{res}t \\ b_1 &= \frac{1}{\pi} \int_0^{2\pi} R(t) \sin(\omega_{res}t) d\omega_{res}t \end{aligned} \right\} \quad (4)$$

**[0073]** As represented in the equations (5) and (6), the gain  $G_{res}$  and the phase  $\phi_{res}$  can be obtained respectively from  $a_1$  and  $b_1$  that form the describing function extracted as described above.

$$G_{res} = \sqrt{a_1^2 + b_1^2} \quad (5)$$

$$\phi_{res} = \arctan \frac{b_1}{a_1} \quad (6)$$

**[0074]** FIG. 7A and FIG. 7B are charts representing a reference respiratory signal and a real respiratory signal respectively. FIG. 7A is a chart representing a reference respiratory signal; FIG. 7B is a chart representing a real respiratory signal. The abscissa denotes the time; the ordinate denotes the signal value of the respiratory signal  $R(t)$ . The cycle of the reference respiratory signal NW is  $T_{res}$ ; the cycle of the real respiratory signal  $R_{rj}(t)$  is  $T_{res} \cdot 1$ . Reference character BL in FIG. 7A and FIG. 7B denotes the base line of each of the reference respiratory signal NW and the real respiratory signal  $R_{rj}(t)$ . The real respiratory signal  $R_{rj}(t)$  is irregular signal. However, for example, when respiratory induction is performed based on the sine wave signal on the basis of the cycle  $T_{res}$  of the reference respiratory signal NW or the reference respiratory signal  $R_{rj}(t)$ , the real respiratory signal  $R_{rj}(t)$  also becomes a cyclic function having a cycle the same as that of the reference respiratory signal  $R_{rj}(t)$ . By utilizing the respi-

ratory characteristics thereof, as is the case with the reference respiratory signal  $R_{rj}(t)$ , also with regard to the real respiratory signal  $R_{rj}(t)$ , there can be calculated a describing function including the pair of coefficients  $a_1$  and  $b_1$ , of the trigonometric functions, that correspond to the 1st-order terms when Fourier series expansion is applied, as represented in the equation (4).

**[0075]** In the case where the motion of the patient 24 is detected and then it is determined whether or not the motion has exceeded a predetermined range, it is only necessary that the cycle  $T_{res} \cdot 1$  of the real respiratory signal  $R_{rj}(t)$  approximately coincides with the cycle  $T_{res}$  of the reference respiratory signal  $R_{rj}(t)$ . By setting predetermined ranges for the gain  $G_{res}$  and the phase  $\phi_{res}$ , the ranges of the gain  $G_{res}$  and the phase  $\phi_{res}$  can be adopted as predetermined ranges. For example, when a patient has a coughing fit, the gain and the phase of the real respiratory signal rapidly change; thus, the gain  $G_{res}$  and the phase  $\phi_{res}$  exceed the predetermined ranges, whereby the motion of the patient caused by the coughing fit can be detected. In addition, when the patient falls into a sleep, the gain of the real respiratory signal gradually becomes small, and the phase of the real respiratory signal gradually loses the correlation with the phase of the reference respiratory signal. Even in this case, by setting appropriate ranges for the gain  $G_{res}$  and the phase  $\phi_{res}$ , there can be detected a fact that the patient has fallen into a sleep or a sign that the patient is going to fall into a sleep.

**[0076]** As described above, in the particle beam therapy system according to Embodiment 1, there are provided the irradiation management apparatus 32 that controls the scanning electromagnet 3, based on the desired irradiation position coordinates  $P_i$  of the charged particle beam 1; the position monitor 7 that measures the measured position coordinates  $P_s$  of the charged particle beam 1; and the interlock information inputting device 84 that generates an interlock signal for stopping irradiation of the charged particle beam 1, when a contingency occurs. The irradiation management apparatus 32 is provided with a command value generator that outputs the control input  $I_o$  (Ir) to the scanning electromagnet 3, based on the desired irradiation position coordinates  $P_i$  and the correction data  $I_a$  generated on the basis of the measured position coordinates  $P_s$ , measured by the position monitor 7 in the preliminary irradiation in which the excitation pattern of the scanning electromagnet 3 is the same as that of the actual irradiation plan, and the desired irradiation position coordinates  $P_i$ ; and a stop step storage memory that stores a stop step corresponding to the desired irradiation position coordinates  $P_i$  at which irradiation of the charged particle beam 1 stops, when the interlock signal is generated by the interlock information inputting device 84. When irradiation of the charged particle beam 1 is resumed, the irradiation management apparatus 32 performs idle operation in which the scanning electromagnet 3 is controlled, with the charged particle beam 1 unirradiated, from a start step, which is situated prior to the stop step and is different from the initial step corresponding to the initial desired irradiation position coordinates in actual irradiation, to the stop step, and then the irradiation management apparatus 32 irradiates the charged particle beam 1 from the desired irradiation position coordinates  $P_i$  corresponding to the stop step; therefore, in the case where emergency-stop processing is performed during therapy, idle operation is carried out, based on irradiation command data including a control input to the scanning electromagnet 3, from a start step,

which is situated prior to the stop step and is different from the initial step, and beam irradiation is started from an irradiation position where the irradiation has been interrupted. As a result, the effect of the hysteresis of the scanning electromagnet 3 is eliminated, so that high-accuracy beam irradiation can be resumed from the irradiation position where the irradiation has been interrupted.

#### Embodiment 2

[0077] In Embodiment 1, there has been described idle operation of the scanning electromagnet 3 at a time when irradiation is resumed after therapy has been interrupted; however, in Embodiment 2, there will be described a method of initializing the scanning electromagnet 3 before the idle operation thereof.

[0078] FIG. 8 is a schematic diagram representing a fact that a diseases site is scanned with a beam along a beam path in a particle beam therapy system according to Embodiment 2 of the present invention. The charged particle beam 1 scanned by the scanning electromagnet 3 is irradiated onto each of the layers (slices) of a diseased site such as a cancer, which is the irradiation subject 15, along an irradiation path 14 (referred to also as a beam path). In the scanning-type particle beam therapy system 51, the beam path 14 for each layer is generated by use of a treatment planning apparatus. In the treatment planning apparatus, an optimum treatment plan is generated in such a way that the cancer diseased site is reached through as short path as possible and there exists no unnecessary irradiation onto normal tissues. In the treatment planning apparatus, there is incorporated a computer that performs the optimization; the optimum path is obtained by use of the computer. A doctor, who is a main person (person in charge) for the therapy, eventually determines whether or not the obtained path is optimum. The X-direction scanning electromagnet 3x and the Y-direction scanning electromagnet 3y are controlled by the irradiation management apparatus 32 in such a way that the charged particle beam 1 is scanned along the generated beam path 14, and the scanning electromagnet power source 4 (referred to also as a pattern power source) supplies a driving current (command current).

[0079] FIG. 9A and FIG. 9B are charts representing the hysteresis characteristics of a scanning electromagnet in a particle beam therapy system according to Embodiment 2. FIG. 9A represents the hysteresis characteristics of the X-direction scanning electromagnet 3x; FIG. 9B represents the hysteresis characteristics of the Y-direction scanning electromagnet 3y. As represented in FIG. 9A and FIG. 9B, the magnetic material, which is a material of the scanning electromagnet, has hysteresis characteristics. In FIG. 9A and FIG. 9B, the abscissa denotes the magnetic-field intensity H of a magnetic field generated by an inputted command current; the ordinate denotes the magnetic flux density B. "αx" denotes a maximum hysteresis curve of the X-direction scanning electromagnet 3x; "αy" denotes a maximum hysteresis curve of the Y-direction scanning electromagnet 3y. The hysteresis characteristics denote the relationship between the magnetic-field intensity H and the magnetic flux density B in which even when the magnetic-field intensity H is determined, the magnetic flux density B is not uniquely determined simply based on the magnetic-field intensity H, as showed in FIG. 9A and FIG. 9B. In order to realize the beam path 14 optimized for each diseased site, the scanning electromagnet 3 is excited in accordance with each of patterns that vary depending on diseased sites. Accordingly, the BH hys-

teresis curves on the BH plane, along which the magnetization characteristics of the scanning electromagnet 3 follow, vary depending on the beam paths.

[0080] For example, in the case where the scanning electromagnet 3 is excited in a given pattern, the magnetic characteristic of the scanning electromagnet 3 follows the BH hysteresis curves such as thin solid lines 26a and 27a in FIG. 9A and FIG. 9B. Because the particle beam therapy system 51 deals with a human body, the irradiation is stopped when a contingency occurs. The coordinates of a point, on the hysteresis curve, that corresponds to the stop position (stop spot) where the irradiation has been stopped are (P1x, P1y). After that, the irradiation is resumed after the safety is confirmed. When the irradiation is resumed, it is required to resume the irradiation after the condition of the scanning electromagnet 3 at a time when irradiation has not been stopped is reproduced. In order to reproduce the condition of the scanning electromagnet 3, it is required to reproduce the same magnetic flux density B, the same magnetic-field intensity H, and the same magnetic-field vs. time gradient dH/dt. Accordingly, it is effective that before the irradiation of the charged particle beam 1 is started, the scanning electromagnet 3 is initialized, for example, as B=0, H=0, and dH/dt=0, in such a way that the irradiation is always started with the same condition of the scanning electromagnet 3, i.e., in such a way that when the condition of the scanning electromagnet 3 is represented on the BH plane, the BH hysteresis curve always starts from the same point (P1x, P1y). The broken lines 26b and 27b are the BH hysteresis curves at a time when the scanning electromagnet 3 is controlled with irradiation unstopped. The initialization of the scanning electromagnet 3 and the idle operation explained in Embodiment 1 enable the condition of the scanning electromagnet 3 to always start from the same point (P1x, P1y) when represented on the BH plane.

[0081] With regard to the initialization of the scanning electromagnet 3, there is given a predetermined excitation pattern, for example, in such a way that the scanning electromagnet 3 is excited up to +H-direction maximum value, which is within the specification range, and then is excited up to -H-direction maximum value, which is within the specification range. By, as described above, exciting the scanning electromagnet 3 up to the maximum values, it can be expected that the residual magnetism in the magnetic material of the scanning electromagnet 3 is eliminated. The initialization of the scanning electromagnet 3 is not limited to the condition in which B=0, H=0, and dH/dt=0; there may exist an offset, as long as the reproducibility can be ensured.

[0082] In Embodiment 1, there has been explained an example in which irradiation of the scanning electromagnet 3 is not performed before idle operation. In Embodiment 1, although it is rare, a case may occur in which even during idle operation, the effect of the hysteresis of the scanning electromagnet 3 cannot sufficiently be eliminated. In the case where the effect of the hysteresis of the scanning electromagnet 3 is not sufficiently eliminated, the positional accuracy of beam irradiation may be deteriorated to some extent. However, in Embodiment 2, the scanning electromagnet 3 is initialized before idle operation; therefore, the effect of the hysteresis of the scanning electromagnet 3 can sufficiently be eliminated.

[0083] In addition, it is also conceivable that as the method of adjusting the condition of the scanning electromagnet 3, an auxiliary coil is utilized. In the case where the command value for the scanning electromagnet 3 is "0", i.e., in the case where because no driving current is supplied from the scanning

electromagnet power source 4, the scanning electromagnet 3 is not excited, the magnetic flux density B should be "0". However, as represented in FIG. 9A and FIG. 9B, in some cases, due to the hysteresis characteristics, the magnetic flux density B does not become "0". In this situation, an electric current is applied to an auxiliary coil provided in the scanning electromagnet 3 so that the condition thereof is controlled, whereby the magnetic flux density B can be made to be "0" in such a way that the residual magnetism is cancelled. Also in such a manner as described above, beam irradiation can be started with the condition of the scanning electromagnet 3 made always the same (for example, the origin on the BH plane or the stop position (P1x, P1y) in FIG. 9A and FIG. 9B). As described above, the initialization of the scanning electromagnet 3 is not limited to the condition in which B=0; there may exist an offset, as long as the reproducibility can be ensured.

**[0084]** A procedure for stopping and resuming beam irradiation will be explained with reference to FIG. 10. FIG. 10 is a flowchart representing a procedure for stopping and resuming beam irradiation in a particle beam therapy system according to Embodiment 2. The procedure for stopping and resuming beam irradiation according to Embodiment 2 differs from the procedure for stopping and resuming beam irradiation according to Embodiment 1 in that a procedure (the step S10) for initializing the scanning electromagnet 3 is added, and the idle operation where the scanning electromagnet 3 is controlled starts from the initial step in actual irradiation, i.e., from the initial step in the first slice (the step S11: the idle operation procedure).

**[0085]** In the case where a contingency occurs during therapy, the irradiation management apparatus 32 performs the foregoing determination on irradiation stop, based on the interlock signal generated by the interlock information inputting device, and stops the irradiation. The irradiation management apparatus 32 stores the interruption step (the step S1: the stop step storage procedure). The irradiation management apparatus 32 initializes the scanning electromagnet 3 (the step S10: the magnetic-field initialization procedure). The foregoing method can be utilized for initializing the scanning electromagnet 3. After the magnetic-field initialization, the irradiation management apparatus 32 activates the scanning electromagnet power source 4, with a beam unirradiated in the process from the initial step in actual irradiation to the stop step, so as to perform only magnetic-field excitation of the scanning electromagnet 3 (the step S11: the idle operation procedure). As is the case with Embodiment 1, beam irradiation is resumed (the step S3: irradiation start procedure).

**[0086]** By performing idle operation after magnetic-field initialization, the irradiation resumption condition (i.e., the BH hysteresis curve on the BH plane) where  $B=B_0$ ,  $H=H_0$ , and  $dH/dt=H'_0$  can be reproduced. In this regard, however,  $B_0$  denotes the magnetic flux density at a time before irradiation interruption;  $H_0$  denotes the magnetic-field intensity at a time before irradiation interruption;  $H'_0$  denotes the magnetic-field vs. time gradient at a time before irradiation interruption.

**[0087]** As the effect of adopting this sequence, even when irradiation is interrupted halfway, the irradiation can be resumed with the same condition, of the scanning electromagnet 3, that has followed the same BH hysteresis curve; thus, it is made possible to minimize the positional deviation of the irradiation spot. In Embodiment 2, as examples of methods for reproducing the condition, at a time before irradiation interruption, where  $B=B_0$ ,  $H=H_0$ ,  $dH/dt=H'_0$ , there

have been described a method where excitation is carried out up to the maximum level and then is carried out up to the minimum level and a method where an auxiliary coil is utilized; however, there exists no intention to limit the present invention thereto, because the initialization method in which the condition where  $B=B_0$ ,  $H=H_0$ ,  $dH/dt=H'_0$  can be reproduced when therapy is resumed has the same effect.

**[0088]** However, the particle beam therapy system 51 according to Embodiment 2 performs magnetic-field initialization before idle operation; therefore, in Embodiment 2, the effect of the hysteresis of the scanning electromagnet 3 can more sufficiently be eliminated than in Embodiment 1.

**[0089]** In the case of an irradiation method in which the charged particle beam 1 is stopped when slices are changed and the charged particle beam 1 is continuously irradiated when irradiation is performed within a single and the same slice, it is made possible that a magnetic-field sensor is provided in the scanning electromagnet 3 and through the magnetic-field sensor, the residual magnetism can be measured before a beam is irradiated onto each slice. By preliminarily measuring the residual magnetism, the initialization of the scanning electromagnet 3 can be performed based on the measured value of the residual magnetism, when the initial step in the slice is resumed before the idle operation. Before the idle operation is performed, the initialization of the scanning electromagnet 3 can be performed based on the measured value of the residual magnetism in the initial step in the slice at which the idle operation is started. Because the initialization of the scanning electromagnet 3 can be performed before the idle operation is performed, operation can be implemented from the initial step in the slice at which beam irradiation has been interrupted or from a step that is predetermined steps prior to the stop step. FIG. 11 represents a procedure for stopping and resuming beam irradiation in the foregoing case.

**[0090]** FIG. 11 is a flowchart representing another procedure for stopping and resuming beam irradiation in a particle beam therapy system according to Embodiment 2. FIG. 11 differs from FIG. 10 in that the step S11 has been replaced by the step S2 explained in Embodiment 1. A magnetic-field sensor measures the magnetic field of the scanning electromagnet 3 at the initial desired irradiation position coordinates  $P_i$  in each of the slices. The irradiation management apparatus 32 performs initialization processing for the scanning electromagnet 3 based on the measured value of the magnetic field at the initial desired irradiation position coordinates  $P_i$  in the slice at which the idle operation is started. In this method, in the case where the irradiation subject 15 is large and hence the number of irradiation steps is large, even when irradiation is interrupted in a latter slice, idle operation is performed not from the initial step in actual irradiation but from the initial step in the slice at which the irradiation has been interrupted; therefore, the time for the idle operation can be reduced.

**[0091]** In Embodiment 1, it has been explained that although in view of the reproducibility, it is desirable to perform the idle operation from the initial step for a given slice, a considerable effect can still be obtained even when the idle operation is performed from a step, empirically confirmed, that is predetermined steps (predetermined spots) prior to the stop step. By utilizing this method, the effect of the hysteresis of the scanning electromagnet 3 can sufficiently be eliminated not only in the case where initialization processing for the scanning electromagnet 3 is performed based on the measured value of the magnetic field at the initial desired

irradiation position coordinates  $P_i$  in a given slice, but also in the case where the initialization processing for the scanning electromagnet 3 is performed under a predetermined initialization condition, for example, where  $B=0$ ,  $H=0$ , and  $dH/dt=0$ ; therefore, the irradiation accuracy can fall within an allowable range.

[0092] In each of Embodiments 1 and 2, there has been explained an irradiation method in which the charged particle beam 1 is stopped when slices are changed, and the charged particle beam 1 is continuously irradiated when irradiation is performed within a single and the same slice; however, the present invention can be applied to other irradiation methods such as the spot-scanning method in which the charged particle beam 1 is stopped for each irradiation spot and the raster-scanning method.

#### DESCRIPTION OF REFERENCE NUMERALS

- [0093] 1: charged particle beam
- [0094] 3, 3a, 3b, 3x, 3y: scanning electromagnet
- [0095] 7: position monitor
- [0096] 15: irradiation subject
- [0097] 24: patient
- [0098] 32: irradiation management apparatus
- [0099] 51: particle beam therapy system
- [0100] 54: accelerator
- [0101] 78: patient sensor
- [0102] 84, 84a, 84b: interlock information inputting device
- [0103] Ia: current correction data
- [0104] Io, Ir: command current
- [0105]  $P_i$ : desired irradiation position coordinates
- [0106]  $P_s$ : measured position coordinates

1. A patient respiration evaluation method in which a displacement between a real respiratory signal indicating real respiration of a patient and a reference respiratory signal indicating desired respiration of the patient is evaluated, the patient respiration evaluation method comprising:

- a step of obtaining a first gain and a first phase of a describing function corresponding to a first-order term in a Fourier series expansion of the reference respiratory signal;
- a step of obtaining a second gain and a second phase of a describing function corresponding to a first-order term in a Fourier series expansion of the real respiratory signal; and
- a step of comparing the first gain with the second gain and/or comparing the first phase with the second phase.

2. The patient respiration evaluation method according to claim 1, further including a step of determining that in the case where the second gain abruptly falls out of a preliminarily set gain threshold range around the first gain and/or the second phase abruptly falls out of a preliminarily set phase threshold range around the first phase, the patient had a fit of coughing.

3. The patient respiration evaluation method according to claim 1, further including a step of determining that in the case where the second gain gradually decreases within the preliminarily set gain threshold range around the first gain or the correlation between the second phase and the first phase decreases in such a way as to exceed a preliminarily set correlation determination range, it is suggested that the patient has fallen asleep or is going to fall asleep.

4. A patient respiration evaluation apparatus in which a displacement between a real respiratory signal indicating real respiration of a patient and a reference respiratory signal indicating desired respiration of the patient is evaluated, the patient respiration evaluation apparatus comprising:

- a gain calculation unit that obtains a first gain and a first phase of a describing function corresponding to a first-order term in a Fourier series expansion of the reference respiratory signal;
- a phase calculation unit that obtains a second gain and a second phase of a describing function corresponding to a first-order term in a Fourier series expansion of the real respiratory signal; and
- a comparison unit that compares the first gain with the second gain and/or that compares the first phase with the second phase.

5. The patient respiration evaluation apparatus according to claim 4, further including a determination unit that determines that in the case where the second gain abruptly falls out of a preliminarily set gain threshold range around the first gain and/or the second phase abruptly falls out of a preliminarily set phase threshold range around the first phase, the patient had a fit of coughing.

6. The patient respiration evaluation apparatus according to claim 4, further including a determination unit that determines that in the case where the second gain gradually decreases within the preliminarily set gain threshold range around the first gain or the correlation between the second phase and the first phase decreases in such a way as to exceed a preliminarily set correlation determination range, it is suggested that the patient has fallen asleep or is going to fall asleep.

\* \* \* \* \*

专利名称(译)	粒子束治疗系统		
公开(公告)号	<a href="#">US20130253845A1</a>	公开(公告)日	2013-09-26
申请号	US13/897085	申请日	2013-05-17
[标]申请(专利权)人(译)	三菱电机株式会社		
申请(专利权)人(译)	三菱电机株式会社		
当前申请(专利权)人(译)	三菱电机株式会社		
[标]发明人	IWATA TAKAAKI SUGAHARA KENGO HARADA HISASHI		
发明人	IWATA, TAKAAKI SUGAHARA, KENGO HARADA, HISASHI		
IPC分类号	A61B5/00		
CPC分类号	A61B5/48 A61N2005/1087 A61N2005/1074 A61N5/1043		
优先权	PCT/JP2011/053367 2011-02-17 WO		
外部链接	<a href="#">Espacenet</a> <a href="#">USPTO</a>		

摘要(译)

目的是消除扫描电磁铁的滞后效应，并且即使在治疗期间进行紧急停止处理的情况下，也从已被中断的照射位置恢复高精度光束照射。提供一种控制扫描电磁铁的照射管理装置；以及互锁信息输入装置，当发生意外事件时，该互锁信息输入装置产生用于停止带电粒子束的照射的互锁信号。当重新开始带电粒子束的照射时，照射管理装置执行空转操作，其中控制扫描电磁体，其中带电粒子束未被照射，从开始步骤开始，该开始步骤位于停止步骤之前并且不同于在实际照射中的初始步骤，到停止步骤，然后从对应于停止步骤的期望照射位置坐标照射带电粒子束。

