# DESCRIPTION

Title of Invention: ACCELERATOR AND PARTICLE THERAPY APPARATUS

## Technical Field

[0001]

The present disclosure relates to an accelerator and a particle therapy apparatus.

## Background Art

[0002]

A particle therapy apparatus that irradiates a tumor with an ion beam obtained by accelerating charged particles such as protons or carbon ions is known. An accelerator that accelerates the charged particles accelerates an ion beam extracted from an ion source or an electron gun until energy required for treatment while controlling an orbit using an electric field and a magnetic field. Typical accelerators for a particle therapy apparatus include a cyclotron, a synchrocyclotron, and a synchrotron that can obtain a beam having an energy of several hundreds MeV order.

[0003]

The cyclotron and the synchrocyclotron accelerate the beam by applying a radiofrequency electric field synchronized with a circulating cycle of the beam to the beam circularly rotated by a static magnetic field. As the beam obtains more energy by the radiofrequency electric field, the closed orbit radius of the beam becomes larger. Then, the beam is extracted from the circumferentially outermost closed orbit after reaching the highest energy. Therefore, there is a problem that the energy of the beam that can be extracted is a single energy.

[0004]

On the other hand, the synchrotron is an accelerator that accelerates the beam while keeping the closed orbit radius of the beam constant by temporally changing the intensity of the magnetic field that deflects the beam and the cycle of the accelerating electric field. In the synchrotron, the closed orbit radius is constant, that is, beams having different energies are accelerated on the same closed orbit, and it is thus possible to perform variable energy extraction in which the energy of the beam to be extracted is variable.

[0005]

In addition, PTL 1 discloses an eccentric trajectory accelerator that enables variable energy to be extracted while using a static magnetic field.

[0006]

PTL 2 discloses a technique for reducing disturbance to a resonant magnetic field due to an extraction channel magnetic field, which is a problem in resonant extraction in which a beam is extracted using a resonant magnetic field.

[0007]

NPL 1 describes, as a method for reducing disturbance that is different from that of PTL 2, a method of correcting a disturbance magnetic field of a first harmonic component in a main magnetic field region due to a regenerator magnetic field of a cyclotron accelerator.

[0008]

NPL 2 describes a technique for optimizing the shape of a main magnetic pole for the purpose of generating a magnetic field distribution required for realizing eccentric beam trajectory arrangement in the eccentric trajectory accelerator described in PTL 1.

Citation List

Patent Literature

[0009]

PTL 1: JP 2020-38797 A

PTL 2: Japanese Patent No. 6612307

Non-Patent Literature

[0010]

NPL 1: "Fast Computation of magnetic shimming ina high field environment", W.Kleeven, European Cyclotron Progress Meeting (2012).

NPL 2: “Development of Magnet Design Method for

Cotangential Trajectory Accelerator”, Kento Nishida, Chishin Hori, Takamichi Aoki, Takamitsu Hae, Proceedings of the 17 th Annual Meeting of Particle Accelerator Society of Japan (2020).

Summary of Invention

Technical Problem

[0011]

An object of the present disclosure is to provide an accelerator and a particle therapy apparatus capable of efficiently and satisfactorily extracting a beam.

Solution to Problem

[0012]

An accelerator according to an aspect of the present disclosure is an accelerator that accelerates an ion beam while causing the ion beam to circulate by a main magnetic field and an acceleration radiofrequency electric field, the accelerator including: a main magnetic field generation device that applies the main magnetic field to a space between a plurality of main magnetic poles arranged to face each other; a beam displacement device that causes the ion beam circulating in a main magnetic field region to which the main magnetic field is applied to be displaced to outside of the main magnetic field region; an extraction channel magnetic field generation device that generates an extraction channel magnetic field to extract the ion beam that has been moved to the outside; and a canceling magnetic field generation device that is provided to be closer to an inner periphery side than the extraction channel magnetic field generation device and generates a canceling magnetic field with a polarity opposite to a polarity of the extraction channel magnetic field.

Advantageous Effects of Invention

[0013]

According to the present invention, it is possible to efficiently and satisfactorily extract a beam.

Brief Description of Drawings

[0014]

[FIG. 1] FIG. 1 is a diagram illustrating a particle therapy system according to a first embodiment of the present disclosure.

[FIG. 2] FIG. 2 is a configuration diagram illustrating a configuration example of an accelerator.

[FIG. 3] FIG. 3 is a longitudinal sectional view along a vertical plane of a main magnet.

[FIG. 4] FIG. 4 is a schematic view illustrating an example of an extraction channel.

[FIG. 5] FIG. 5 is a diagram for explaining extraction of a beam by resonance using a resonant magnetic field generated in a resonant magnetic field region.

[FIG. 6] FIG. 6 is a diagram illustrating an example of an extraction channel magnetic field and a canceling magnetic field.

[FIG. 7] FIG. 7 is a diagram illustrating a structure example of a canceling magnetic field generation device according to the first embodiment of the present disclosure.

[FIG. 8] FIG. 8 is a diagram illustrating an example of canceling magnetic field generation devices according to a second embodiment of the present disclosure.

[FIG. 9] FIG. 9 is a diagram illustrating another example of the canceling magnetic field generation device according to the second embodiment of the present disclosure.

[FIG. 10] FIG. 10 is a diagram illustrating an arrangement example of a canceling magnetic field generation device according to a third embodiment of the present disclosure.

[FIG. 11] FIG. 11 is a diagram illustrating a structure example of the canceling magnetic field generation device according to the third embodiment of the present disclosure.

Description of Embodiments

[0015]

Hereinafter, embodiments of the present disclosure will be described with reference to the drawings

First embodiment

[0016]

FIG. 1 is a diagram illustrating a particle therapy system according to a first embodiment of the present disclosure. The particle therapy system illustrated in FIG. 1 is a particle therapy apparatus for performing particle therapy in which a patient to be treated is irradiated with an ion beam that is a particle beam (hereinafter, also simply referred to as a beam). The particle therapy system includes an accelerator A100 that accelerates and extracts a beam, a beam transport line A110 that transports the beam extracted from the accelerator A100, a treatment room A130 for irradiating a patient A131 with the beam transported by the beam transport line A110, and a control apparatus A140 for controlling the accelerator A100 and the beam transport line A110.

[0017]

The accelerator A100 is a device that generates and extracts a beam of an energy band used for particle therapy. The accelerator A100 includes an ion source system A102 that implants ions to form a beam, a main magnet A101 that internally accelerates the ions from the ion source system A102 as a beam, and an extraction port A103 which is an outlet for taking out and extracting the beam accelerated by the main magnet A101 to the outside.

[0018]

The ion source system A102 is, for example, an internal ion source using a cold cathode or an external ion source using a radiofrequency source. In the present embodiment, the ion source system A102 is an external ion source and is attached to the main magnet A101 as illustrated in FIG. 1. Note that in a case where the ion source system A102 is an internal ion source, a cold cathode electrode serving as a main body of the ion source system A102 is attached inside the main magnet A101 and is further connected to a gas introduction path and a power supply. Also, the type of the ion is not particularly limited and is, for example, a proton or a carbon ion.

[0019]

The main magnet A101 generates a main magnetic field for causing the beam to circulate. The main magnetic field is a magnetic field distribution to be applied to cause the beam to circulate in a predetermined equilibrium trajectory. Specifically, the main magnet A101 is formed to be substantially vertically symmetric and includes therein an acceleration space for accelerating the beam while causing the beam to circulate. The main magnet A101 applies a Lorentz force to the acceleration space by causing the main magnetic field to act on the ions implanted by the ion source system A102 and forms a beam by causing the ions to circulate along a circular trajectory. The beam is accelerated to achieve a desired energy by a radiofrequency electric field generated inside the main magnet A101 and is then extracted to the outside of the accelerator A100 via the extraction port A103. A series of device operations related to ion injection (implantation) and beam acceleration and extraction are controlled by the control apparatus A140.

[0020]

The beam transport line A110 transports the beam extracted from the accelerator A100 to the treatment room A130. The beam transport line A110 comprehensively handles beams having different characteristics for each energy and transports the beams while correcting beam emittances and energy variations of each beam. The beam transport line A110 includes beam pipes A111, A117, A119, and A122 through which a beam passes, bending magnets A112, A115, A118, and A120 for adjusting a traveling direction of the beam, and convergence magnets A113, A114, A116, and A123 for controlling a beam shape.

[0021]

The inside of the beam pipes A111, A117, A119, and A122 is evacuated using a vacuum pump A124 such as an ion pump or a turbo molecular pump to prevent the beam from colliding against neutral gas and being lost. The bending magnets A112, A115, A118 and A120 are arranged such that the beam travels along the beam pipes A111, A117, A119 and A122. The convergence magnets A113, A114, A116, and A123 are configured such that the emittance and energy of the beam can be adjusted by a convergence or divergence effect. The bending magnets A112, A115, A118, and A120 and the convergence magnets A113, A114, A116, and A123 are controlled by the control apparatus A140. Note that although the beam transport line A110 transports a beam from one accelerator A100 to one treatment room A130 in FIG. 1, beams may be transported from one accelerator A100 to a plurality of treatment rooms A130.

[0022]

The treatment room A130 includes a bed A132 for fixing the patient A131 and irradiation devices A133 and A134 for irradiating the patient A131 with the beam transported by the beam transport line A110.

[0023]

The irradiation devices A133 and A134 have a function of changing the shape and the energy distribution of the beam transported by the beam transport line A110 to be suitable for therapy. The irradiation devices A133 and A134 may be configured to include a collimator for scraping off unnecessary portions of a beam, a ridge filter for expanding an irradiation range in a depth direction with respect to a tumor by expanding an energy distribution of the beam, a range shifter for finely adjusting a position which the beam reaches, and various monitors for monitoring a beam irradiation dose and a beam profile, for example, which are arranged therein. Furthermore, the irradiation devices A133 and A134 have an irradiation mechanism for irradiating a desired position with the beam. For example, the irradiation mechanism may be configured to be able to irradiate the treatment target with the beam from an arbitrary angle using a rotatable gantry, and may be configured to include a scanning magnet that deflects the beam.

[0024]

FIG. 2 is a configuration diagram illustrating a configuration example of the accelerator A100, and is a horizontal sectional view taken along a central plane which is a geometric central plane of the accelerator A100 in the up-down direction. Note that in the present embodiment, the accelerator A100 is an accelerator that extracts a beam using a resonant magnetic field, and an eccentric trajectory-type circular accelerator will be described below as an example.

[0025]

The accelerator A100 is an accelerator designed such that a main magnetic field through which a beam passes during acceleration is not symmetric in a circumferential direction and beam orbits of beams having mutually different energies form a set of circular orbits eccentric to each other. The eccentric trajectory-type accelerator A100 forms a trajectory aggregation portion where beam trajectories of beams having mutually different energies are close to each other, and all beams having energies to be extracted pass through a narrow space in the vicinity of the trajectory aggregation portion. Therefore, it is possible to perform variable energy extraction by causing the electric field and a magnetic field for beam extraction to act on the narrow space. Note that since the accelerator A100 uses a static magnetic field, a temporal change in magnetic field intensity is not necessary, and it is possible to achieve size reduction by increasing the intensity of the magnetic field using a superconducting coil for the main magnet.

[0026]

The accelerator A100 includes a displacement unit, a resonant magnetic field region, and a septum magnet as a variable energy extraction mechanism that enables variable energy extraction. The displacement unit and the resonant magnetic field region constitute a beam displacement device. Note that in a case where the septum magnet is configured only of a ferromagnetic body without using a coil, the septum magnet is often referred to as an extraction channel.

[0027]

The displacement unit has a role of drawing out the beam trajectory to the outside of the main magnetic field region by giving perturbation in the horizontal direction (the radial direction of the magnet) to the beam circulating on the eccentric trajectory and causing resonance. The perturbation in the horizontal direction is given by an RF kicker, and the perturbed beam travels on the radially outer peripheral side in a view from an equilibrium trajectory and is affected by the resonant magnetic field. The resonant magnetic field is a higher order magnetic field including at least quadrupole magnetic field components and includes a peeler magnetic field having a magnetic field gradient in a direction of weakening the main magnetic field toward the radially outer peripheral side and a regenerator magnetic field having a magnetic field gradient in a direction of strengthening the main magnetic field toward the radially outer peripheral side. These magnetic fields are formed over a predetermined azimuthal angle region on the outer peripheral side of the maximum extraction energy trajectory. In addition, the peeler magnetic field region is arranged on the upstream side, and the regenerator magnetic field region is arranged on the downstream side, with respect to the beam traveling direction. These two magnetic field regions will be collectively referred to as a resonant magnetic field region. The beam is kicked on the outer peripheral side by passing through the peeler magnetic field region and is kicked on the inner peripheral side by passing through the regenerator magnetic field region. The peeler magnetic field region and the regenerator magnetic field are adjusted to have a tune of about 1 and further have a magnetic field gradient of increasing the intensity toward the radially outer peripheral side. For this reason, the beam gradually moves to the radially outer peripheral side every turn, is more strongly affected by the peeler/regenerator magnetic field region, and is brought into a resonance state in which the amount of kicking gradually increases. Then, a turn separation that is a difference in position in the radial direction through which the beam passes per turn becomes equal to or greater than a specific value, the beam is affected by a septum magnet that generates an extraction magnetic field in the next stage. The septum magnet is used to generate an extraction channel magnetic field with a polarity opposite to that of a main magnetic field that causes the beam to circulate and deflect the beam to an extraction trajectory where the beam is not under influences of the main magnetic field. The beam that has entered the trajectory region where the beam is affected by the septum magnet is deflected to the extraction trajectory by the extraction channel magnetic field and is extracted to the outside of the accelerator through the extraction trajectory.

[0028]

As described above, the accelerator A100 includes the main magnet A101 that generates the main magnetic field for confining the beam therein. The main magnet A101 includes a yoke M201, a main magnetic pole M202, a coil M203, a radio frequency (RF) kicker M204 which is an extraction radiofrequency application device, a peeler magnetic field region M205 and a regenerator magnetic field region M206 which are a resonant magnetic field region, and an extraction channel M207. The yoke M201, the main magnetic pole M202, and the coil M203 are main components of the main magnetic field generation device that generates the main magnetic field.

[0029]

A pair of yoke M201 and main magnetic pole M202 are provided on the upper and lower sides to face each other. The main magnetic pole M202 is provided at an inner peripheral portion of the yoke M201, and the yoke M201 and the main magnetic pole M202 constitute an outer shell of the main magnet A101. The yoke M201 and the main magnetic pole M202 are also used as support members that support the coil M203, the extraction channel M207, and the like. An acceleration space, which is a space for the beam to circulate, is formed inside the main magnet A101 (more specifically, between the pair of main magnetic poles M202 on the upper and lower sides), and the main magnetic pole M202 applies a main magnetic field for causing the beam to circulate in the acceleration space. The main magnetic field is not symmetrical in the circumferential direction, and the accelerator A100 is designed such that beam trajectories of beams having mutually different energies form a set of mutually eccentric circular trajectories. The acceleration space is evacuated to reduce a loss due to collisions of the beam against neutral particles. Note that the yoke M201 and the main magnetic pole M202 are formed substantially vertically symmetrically with respect to the central plane, and in this case, the traveling plane through which the beam travels substantially coincides with the central plane of the accelerator A100.

[0030]

The yoke M201 is formed with an extraction port through-hole M208 into which an extraction port A103 for extracting a beam to the outside is inserted. In addition, an acceleration electrode M210 that generates an acceleration radiofrequency electric field to accelerate the beam is arranged inside the main magnet A101, and the acceleration electrode M210 is connected to a rotating capacitor M211 for frequency modulation provided outside the main magnet A101. The acceleration radiofrequency electric field is an electric field that gives energy to the beam by applying a radiofrequency electric field synchronized with the circulating cycle of the beam. The rotating capacitor M211 has a counter electrode capable of changing the effective area of the counter electrode by rotation, and the capacitance is changed by changing the area using the rotating capacitor driving power machine M212. Once the capacitance of the rotating capacitor M211 changes, the resonant frequency of the acceleration electrode M210 is changed, thereby enabling frequency modulation of the acceleration radiofrequency electric field in accordance with the beam energy. The acceleration electrode M210 and the rotating capacitor M211 are connected via an acceleration electrode through-hole M209 formed in the yoke M201. Note that a through-hole may be formed as needed in the yoke M201 separately from the extraction port through-hole M208 and the acceleration electrode through-hole M209. For example, the yoke M201 may be provided with a through-hole for monitoring the beam.

[0031]

The coil M203 is a pair of superconducting coils, and each superconducting coil is arranged substantially plane-symmetrically with respect to a central plane M233 (see FIG. 3), which is a geometric center section in the up-down direction, and is provided along the inner periphery of the yoke M201.

[0032]

FIG. 2 illustrates a geometric center position M231 of the main magnet A101 and an ion injection position M232. In a case where the yoke M201 and the coil M203 are substantially circumferentially symmetric, for example, the geometric center position M231 is the center position thereof. The injection position M232 is a position shifted from the geometric center position M231 and corresponds to the center of the closed orbit along which the beam circulates. In addition, FIG. 2 illustrates a beam closed orbit M221 along which the beam having the lowest energy to be extracted from the accelerator A100 circulates and a beam closed orbit M222 along which the beam having the highest energy to be extracted from the accelerator A100 circulates. The lowest energy is, for example, 70 MeV, and the highest energy is, for example, 230 MeV.

[0033]

The RF kicker M204 is a displacement unit that applies an extraction radiofrequency electric field for extracting a beam to the beams of all energies to be extracted to thereby cause the beam circulating in the main magnetic field region to which the main magnetic field is applied to be displaced to outside. The main magnetic field region is a region through which the beam passes when the beam is accelerated to predetermined energy by the radiofrequency electric field, and is a set of equilibrium trajectories of each energy.

[0034]

The peeler magnetic field region M205 and the regenerator magnetic field region M206 configure a resonant magnetic field region in which a resonant magnetic field that gives resonance to the beam that has been displaced to the outside of the main magnetic field region by the RF kicker M204 is formed. The resonant magnetic field region is arranged in a predetermined azimuthal angle region at an outer peripheral portion (specifically, closer to the outer peripheral side than the beam closed orbit M222 having the highest energy) of the main magnetic field region. The peeler magnetic field region M205 is arranged on the side further upstream than the regenerator magnetic field region M206 with respect to the beam traveling direction. A peeler magnetic field having a magnetic field gradient in a direction of weakening the main magnetic field toward the radially outer peripheral side is formed in the peeler magnetic field region M205, and a regenerator magnetic field having a magnetic field gradient in a direction of strengthening the main magnetic field toward the radially outer peripheral side is formed in the regenerator magnetic field region M206. The peeler magnetic field acts on the beam such that the beam is caused to move radially outward, and the regenerator magnetic field acts on the beam such that the beam is caused to move radially inward.

[0035]

The extraction channel M207 is a device that generates an extraction channel magnetic field for extracting the beam to the outside in the radial direction. Specifically, the extraction channel magnetic field is a magnetic field used when a beam accelerated to reach a predetermined energy is separated to a region where the beam is not affected by the main magnetic field. The accelerated beam is set to have appropriate bipolar magnetic field components and quadrupole magnetic field components such that the beam is stably transported to the extraction port. The extraction channel magnetic field generation device is a device that generates the extraction channel magnetic field. The extraction channel magnetic field generation device is arranged on the downstream side of the resonant magnetic field region with respect to the traveling direction of the extracted beam and stably extracts the beam while adjusting the extraction trajectory of the extracted beam with the bipolar magnetic field components and giving appropriate convergence and divergence to the extracted beam with the quadrupole magnetic field components. The extraction channel M207 in the present embodiment is arranged such that the radial position thereof is located closer to the outer peripheral side than the