peeler magnetic field region M205 and the regenerator magnetic field region M206. Also, the extraction channel M207 is arranged on the side further downstream than the peeler magnetic field region M205 with respect to the beam traveling direction.

[0036]

FIG. 3 is a longitudinal sectional view taken along a vertical plane of the main magnet A101, and more specifically, is a longitudinal sectional view taken along a vertical plane extending in a downward direction in the drawing (a direction at an azimuth angle of -90°) from the central plane M233 in FIG. 2.

[0037]

FIG. 3 schematically illustrates the yoke M201, the main magnetic pole M202, the coil M203, the extraction channel M207, and a canceling magnetic field generation devices M214, which will be described later. Furthermore, the central plane M233, which is a geometric central plane in the up-down direction, of the main magnet A101 and an axial direction M234 of the main magnet A101 facing a direction perpendicular to the central plane M233 are illustrated. In FIG. 3, the acceleration region where the beam is accelerated is present on the inner peripheral side in the radial direction, and the extraction trajectory region before the beam is extracted after the beam leaves the acceleration region is present on the outer peripheral side in the radial direction.

[0038]

The extraction channel M207 is formed to have a pair of one or more magnetic materials on upper and lower sides and has a function of weakening the main magnetic field generated in the substantially axial direction M234. In the example of FIG. 3, the extraction channel M207 includes an extraction channel partitioning wall portion M207a and an extraction channel adjustment portion M207b.

[0039]

The extraction channel partitioning wall portion M207a is a partitioning wall portion that is formed of a magnetic material extending vertically symmetrically in the substantially up-down direction from the central plane M233 and is arranged to serve as a partitioning wall for the inside and the outside in the radial direction. Since the extraction channel partitioning wall portion M207a is formed of a magnetic material, magnetic permeability is sufficiently higher than that of the surroundings. For this reason, magnetic fluxes in the vicinity are attracted to the extraction channel partitioning wall portion M207a, and the magnetic flux density in the region adjacent to the inside and outside in the radial direction in which the magnetic fluxes are attracted decreases. It is thus possible to cause the main magnetic field to suddenly drop in the vicinity of the extraction channel partitioning wall portion M207a and to pull apart the beam from the main magnetic field.

[0040]

The extraction channel adjustment portion M207b is formed of a pair of magnetic materials arranged vertically symmetrically with the central plane M233 interposed therebetween and has a function of guiding the beam to the extraction port A103 while controlling convergence and divergence.

[0041]

An extraction channel magnetic field that realizes a desired arrival position, shape, and the like of the beam is generated by adjusting the positions and the shapes of the extraction channel partitioning wall channel portion M207a and the extraction channel adjustment portion M207b.

[0042]

FIG. 4 is a schematic view illustrating an example of the extraction channel M207.

[0043]

As illustrated in FIG. 4, the shape of the extraction channel M207 in the beam traveling direction in which the beam travels is a shape obtained by extending a sectional shape in the substantially vertical direction along the beam traveling direction of the extraction trajectory. The extraction trajectory of the beam is a trajectory before the beam is extracted after the beam leaves the closed orbit, and the beam traveling direction of the extraction trajectory is set to spread to the outer peripheral side in a view from the center of the main magnet A101 with respect to the closed orbit M235. Due to the aforementioned shape of the extraction channel M207, the beam is gradually pulled apart from the center of the main magnetic field as the beam further travels. Since the magnetic field intensity of the main magnetic field further decreases as the beam further moves to the outer peripheral side in the extraction channel M207, the beam is subjected to divergence in the horizontal direction by a strong magnetic field gradient. In a case where the divergence in the horizontal direction is excessive, the beam is corrected using a magnetic field generated in the extraction trajectory by the pair of extraction channel adjustment portions M207b on the upper and lower sides. Therefore, the extraction channel M207 has different sectional shapes at each position in the beam traveling direction, and a magnetic field distribution corresponding to the traveling of the beam along the extraction trajectory is generated.

[0044]

FIG. 5 is a diagram for explaining resonant extraction of a beam using a resonant magnetic field formed in a resonant magnetic field region.

[0045]

As illustrated in FIG. 5, the peeler magnetic field region M205 and the regenerator magnetic field region M206, which are resonant magnetic field regions, are present on the side further outward in the radial direction than the beam closed orbits M221 and M222. Therefore, the beam is not affected by the resonant magnetic field in a state where the RF kicker M204 does not operate. Once the RF kicker M204 operates and the extraction radiofrequency electric field generated by the RF kicker M204 is applied to the beam, the trajectory of the beam is displaced in the horizontal direction, and the beam passes through the resonant magnetic field region. As a result, the beam reaches the side further outward than the beam closed orbits M221 and M222 as illustrated as beam trajectories M221a and M222a. Then, once the beam reaches a position closer to the outer peripheral side than the extraction channel partitioning wall portion M207a (see FIG. 3) of the extraction channel M207, the beam is pulled apart from the main magnetic field and is guided along the extraction trajectory M223 to the extraction port A103.

[0046]

At this time, since the beam passes the closed orbit located further inward as the energy of the beam is lower, more trajectory displacement is needed for the beam to reach the inlet of the extraction channel M207. On the other hand, a low-energy beam has a smaller momentum than that of a high-energy beam and thus has a smaller amount of kicking at the same magnetic field intensity. Therefore, it is more difficult for the low-energy beam to satisfy beam extraction conditions than the high-energy beam, and extraction efficiency of the low-energy beam is degraded. In order to improve emission efficiency of the low-energy beam, it is only necessary to reduce the required amount of trajectory displacement by causing the extraction channel M207 to approach the beam closed orbit M221 of the lowest energy.

[0047]

However, if the extraction channel M207 is caused to approach the beam closed orbit M221 of the lowest energy, a disturbance magnetic field generated on the radially inner peripheral side on the central plane M233 by the extraction channel M207 increases. In a case where the extraction channel M207 includes the extraction channel partitioning wall portion M207a illustrated in FIG. 3, in particular, the distance from the magnetic material forming the extraction channel M207 to the peeler magnetic field region M205 is short, and the extraction channel M207 thus generates a high-intensity disturbance magnetic field in the peeler magnetic field region M205. This disturbance magnetic field disturbs the peeler magnetic field, and a beam behavior during resonance is significantly likely to be affected by the peeler magnetic field. For this reason, once the high-intensity disturbance magnetic field is generated in the peeler magnetic field region M205, the peeler magnetic field deviates from a desired magnetic field distribution, and it becomes difficult to satisfactorily extract the beam.

[0048]

On the other hand, the accelerator A100 includes the canceling magnetic field generation devices M214 as illustrated in FIG. 3 in order to cancel out the high-intensity disturbance magnetic field generated in the peeler magnetic field region M205 by the extraction channel M207 in the present embodiment.

[0049]

The canceling magnetic field generation devices M214 are devices that generate a canceling magnetic field for canceling out the disturbance magnetic field generated in the peeler portion resonant magnetic field region by the extraction channel M207. The canceling magnetic field has a polarity opposite to that of the disturbance magnetic field generated in the peeler resonant field both devices by the extraction channel.

[0050]

The canceling magnetic field generation devices M214 are devices that generate a magnetic field for generating a canceling magnetic field and can be configured of any of or a combination of a ferromagnetic body, a coil, and a permanent magnet. In the present embodiment, description will be given using an example in which the canceling magnetic field generation devices M214 are configured of a ferromagnetic material such as iron. In addition, a plurality of canceling magnetic field generation devices M214 are arranged plane-symmetrically with respect to the central plane M233. Also, the canceling magnetic field generation devices M214 are arranged such that the canceling magnetic field generation devices M214 overlap the peeler magnetic field region M205 in a view from the up-down direction. With this arrangement, it is possible to accurately cancel out the disturbance magnetic field generated by the extraction channel M207.

[0051]

FIG. 6 is a diagram illustrating an example of a disturbance magnetic field (solid line) and a canceling magnetic field (dashed line) by the extraction channel. Note that in FIG. 6, the vertical axis represents the magnetic field intensity and the horizontal axis represents the position in the radial direction on the central plane M233. More specifically, the horizontal axis represents the position in the radial direction along the downward direction in the drawing (direction of azimuth angle of -90°) from the geometric center position M231 of the main magnet A101 illustrated in FIG. 2. In FIG. 6, the left direction is the outer peripheral side of the main magnet A101, the right direction is the inner peripheral side of the main magnet A101, and the beam moves from the inner peripheral side in the order of the acceleration region, the resonant magnetic field region, and the extraction trajectory region and is extracted to the outside of the accelerator A100.

[0052]

An extraction channel partition M207a is provided at the boundary between the resonant region and the extraction trajectory region. As for the magnetic field distribution in the extraction trajectory region, an extraction channel magnetic field having a polarity opposite to that of the strong main magnetic field is formed in the vicinity of the extraction channel partitioning wall portion M207a as illustrated in FIG. 6, and the beam is thereby pulled apart from the main magnetic field. However, an extraction channel magnetic field with a similar strong opposite polarity is generated in the resonant region on the inner peripheral side of the extraction channel partitioning wall portion M207a as well, and this leads to a disturbance magnetic field that disturbs the resonance state of the beam. If a canceling magnetic field that cancels out the extraction channel magnetic field in the resonant region as illustrated in FIG. 6 is generated, then it is possible to obtain a satisfactory resonance state of the beam.

[0053]

In the example of FIG. 3, the canceling magnetic field generation devices M214 are supported by the main magnet A101 and the like by a non-magnetic body (not illustrated) and are arranged in a gap between the pair of main magnetic poles M202 on the upper and lower sides. As a result, the canceling magnetic field generation devices M214 can be installed in the vicinity of the region where the beam travels. However, the canceling magnetic field generation devices M214 are not limited to this configuration and may be arranged in contact with the main magnetic pole M202. However, in a case where the main magnetic pole M202 and the canceling magnetic field generation devices M214 are integrally formed, the canceling magnetic field generation devices M214 and the central plane M233 are separated from each other, and the magnetic field intensity per unit volume of the canceling magnetic field in the central plane M233 thus decreases. There is a concern that if the magnetic body (ferromagnetic material) forming the canceling magnetic field generation devices M214 is increased in order to compensate for this, unevenness of the surface of the main magnetic pole M202 may become severe, and it may become difficult to process the main magnetic pole M202. In addition, there is also a concern that if the canceling magnetic field generation devices M214 are separated from each other, the generation range in which the canceling magnetic field generation devices M214 generate the peeler magnetic field is widened, and the canceling magnetic field generation devices M214 may thus become a factor of a disturbance magnetic field for another region such as a main magnetic field region. Since a device for beam extraction, a device for beam monitoring, and the like are typically provided in the vicinity of the trajectory aggregation portion of the beam trajectory, in particular, there is also a concern that magnetic interference from the canceling magnetic field generation devices M214 increases. Therefore, it is desirable that the canceling magnetic field generation devices M214 be arranged in the vicinity of the central plane M233 such that a sufficient effect can be obtained with a small amount of magnetic body.

[0054]

FIG. 7 is a diagram illustrating a structure example of the canceling magnetic field generation devices M214. In FIG. 7, only one of the pair of canceling magnetic field generation devices M214 arranged on the upper and lower sides with the central plane M233 sandwiched therebetween is illustrated. Also, FIG. 7(a) is a plan view seen from a side opposite to the central plane M233, FIG. 7(b) is a plan view seen from the right side of FIG. 3, FIG. 7(c) is a plan view seen from a direction perpendicular to FIG. 3, and FIG. 7(d) is a perspective view seen from the side of the central plane M233.

[0055]

The canceling magnetic field generation devices M214 have a curved shape along the peeler magnetic field region M205 illustrated in FIG. 4 and are arranged to sandwich a region (at least a part of the peeler magnetic field region M205) as a target where the disturbance magnetic field is to be canceled out. The shape (such as the thickness at each position) of the canceling magnetic field generation devices M214 is determined in accordance with the intensity distribution of the disturbance magnetic field formed in the peeler magnetic field region M205 by the extraction channel M207. For example, the thickness of the canceling magnetic field generation devices M214 is designed to change along both the circumferential direction and the radial direction and obtain a desired peeler magnetic field.

[0056]

Examples of a method for determining the shape of the canceling magnetic field generation device M214 include a repetitive method of repeating numerical calculation and shape change. In this method, a magnetic field generated by the extraction channel at each position and a canceling magnetic field are calculated through numerical calculation, and the shape of the canceling magnetic field generation devices M214 is adjusted such that the disturbance magnetic field due to the extraction channel is canceled out. Finite element analysis or the technique described in NPL 1 may be used for the numerical calculation of the magnetic field and the canceling magnetic field generated by the extraction channel. In a case where the finite element analysis is used, it may be assumed that the main magnet A101, the extraction channel M207, and the canceling magnetic field generation devices M214 are substantially axisymmetric in order to curb an increase in calculation time. In this case, the shape of the canceling magnetic field generation devices M214 may be corrected in consideration of the shape being non-axisymmetric after the shape of the canceling magnetic field generation devices M214 is determined using the assumption.

[0057]

Note that NPL 2 describes a method of generating a desired magnetic field distribution by deforming the shape of the main magnetic pole M202 in the main magnet A101. In this method, a difference between a magnetic field distribution generated by the main magnet of the eccentric trajectory accelerator and obtained through measurement or calculation and a target magnetic field distribution is calculated first, and then the difference is removed by adding or removing the magnetic material to or from the main magnetic pole surface of the main magnet. Specifically, the optimum arrangement of the magnetic material to be added to or removed from the surface of the main magnetic pole is calculated by inverse analysis based on the least squares method, and the arrangement is reflected to a numerical calculation model or the like, thereby calculating the shape of the main magnet that generates a non-uniform magnetic field distribution like that of an eccentric trajectory accelerator. This method may be used together when the shape of the canceling magnetic field generation devices M214 in the present embodiment is determined. For example, it is possible to further reduce the disturbance magnetic field by performing optimization of the shape of the main magnetic pole M202 using the method descried in NPL 2 after the approximate shape of the canceling magnetic field generation device is determined using an infinite element analysis or the like such that the disturbance magnetic field is substantially cancelled out. In addition, the method described in NPL 2 may be directly applied to the determination of the shape of the canceling magnetic field generation devices M214 in the present embodiment.

[0058]

Note that the magnetic field distribution of the magnetic fields formed by the extraction channel M207 and the main magnet A101 is also changed if the shape of the canceling magnetic field generation devices M214 is changed, and further, the magnetic field distribution of the magnetic field formed by the canceling magnetic field generation devices M214 is changed if the shape of the extraction channel M207 is changed. Therefore, repetitive processing is often required to determine the shape of the canceling magnetic field generation devices M214.

[0059]

In the example of FIG. 3, the canceling magnetic field generation devices M214 are installed in the vicinity of the region where the beam travels, and influences of the canceling magnetic field generation devices M214 thus have high sensitivity to the arrangement position. Therefore, the accelerator A100 may have a jig for accurately arranging the canceling magnetic field generation devices M214 at designed positions, or a position adjustment mechanism capable of finely adjusting the positions of the canceling magnetic field generation devices M214. Also, the canceling magnetic field generation devices M214 may be integrated with the RF kicker M204, the extraction channel M207, or the like. In a case where the canceling magnetic field generation device M214 is integrated with the extraction channel M207, in particular, the canceling magnetic field generation devices M214 can be attached to the main magnet A101 together with the extraction channel M207 after the relative position with the extraction channel M207 is adjusted outside the main magnet A101. Moreover, the canceling magnetic field generation devices M214 may be fixed to the main magnetic pole M202 of the main magnet A101. In any case, since a large attractive force from the main magnet A101 is generated in the canceling magnetic field generation devices M214, the canceling magnetic field generation devices M214 are fixed using a non-magnetic material having high strength. A material such as stainless steel or carbon fiber reinforced plastic, for example, may be used for the jig or the position adjustment mechanism described above.

[0060]

In the eccentric trajectory-type circular accelerator, the low-energy beam circulates on the side further inward than the high-energy beam. In addition, the amount of displacement of the beam from the closed orbit due to the peeler magnetic field is smaller as the energy of the beam is smaller. Therefore, it is more difficult to extract the beam as the energy of the beam is lower. For efficient extraction of the low-energy beam, it is necessary to arrange the extraction channel M207 at a location close to the trajectory aggregation portion of the beam trajectory.

However, if the extraction channel M207 is located at a position close to the trajectory aggregation portion, the peeler magnetic field is disturbed by the disturbance magnetic field generated by the extraction channel M207, and it is not possible to satisfactorily extract the beam.

[0061]

If the configuration described in the present embodiment is adopted, the canceling magnetic field generation devices M214 provided on the inner peripheral side of the extraction channel M207 can cancel out the disturbance magnetic field generated in the peeler portion by the extraction channel M207 with the canceling magnetic field with the polarity opposite thereto. As a result, it is possible to reduce the disturbance to the peeler magnetic field when the extraction channel M207 is located at a position close to the peeler portion. Therefore, it is possible to efficiently and satisfactorily extract the beam.

[0062]

Also, the canceling magnetic field generation devices M214 are arranged such that the canceling magnetic field generation devices M214 overlap the peeler magnetic field region M205 in the present embodiment. Therefore, it is possible to more appropriately cancel out the disturbance magnetic field formed by the extraction channel generated in the peeler magnetic field region 205 which is likely to affect a behavior of the beam.

[0063]

In addition, it is possible to cancel out the extraction channel magnetic field even in a case where the extraction channel partitioning wall portion M207a which greatly affects the peeler magnetic field region 205 is present, and to thereby efficiently and satisfactorily extract the beam in the present embodiment.

[0064]

Furthermore, since the canceling magnetic field generation devices M214 are arranged at positions away from the main magnetic pole M202, the canceling magnetic field generation devices M214 can be arranged at positions close to the central plane M233 in the present embodiment. Therefore, it is possible to reduce influences of the canceling magnetic field generation devices M214 on the surroundings.

[0065]

In addition, since the canceling magnetic field generation devices M214 are formed of a ferromagnetic body such as iron, it is possible to cancel out a high-intensity disturbance magnetic field with a relatively small volume in the present embodiment.

[0066]

In addition, since the canceling magnetic field generation devices M214 are determined in accordance with the magnetic field distribution of the disturbance magnetic field generated in the resonance magnetic field region, it is possible to appropriately cancel out the disturbance magnetic field in the present embodiment.

[0067]

Also, the beam displacement device applies disturbance to the beam that has been displaced outward to generate a peeler magnetic field that causes the beam to move outward in the radial direction in the present embodiment. Therefore, it is possible to more satisfactorily extract the beam.

[0068]

Also, the beam displacement device generates a regenerator magnetic field that gives disturbance to the beam that has been displaced outward to cause the beam to move to inside, generates the peeler magnetic field on the upstream side, and generates the regenerator magnetic field on the downstream side, with respect to the beam traveling direction in the present embodiment. Therefore, it is possible to more satisfactorily extract the beam.

Second embodiment

[0069]

The present embodiment is different from the first embodiment in that an accelerator A100 includes canceling magnetic field generation devices formed of permanent magnets instead of the canceling magnetic field generation device M214 formed of the ferromagnetic material. Hereinafter, configurations different from those in the first embodiment will be mainly described.

[0070]

FIG. 8 is a diagram illustrating an example of the canceling magnetic field generation devices according to the present embodiment and schematically illustrates a longitudinal section along a vertical plane of a main magnet A101 in the vicinity of a central plane M233.

[0071]

As illustrated in FIG. 8, a plurality of (in the drawing, a pair of) canceling magnetic field generation devices M241 formed of permanent magnets are arranged plane-symmetrically with respect to the central plane M233 such that a beam traveling direction is sandwiched therebetween. In addition, the canceling magnetic field generation devices M241 are arranged to have the same polarity as that of a magnetic field generated by the main magnet A101, that is, a polarity opposite to a disturbance magnetic field generated by an extraction channel M207. As a result, it is possible to reduce the disturbance magnetic field generated by the extraction channel M207 with a canceling magnetic field generated by the canceling magnetic field generation devices M241 similarly to the first embodiment in the present