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(54) PARTICLE ACCELERATOR SYSTEM WITH FRACTAL MAGNETIC FIELD GEOMETRY

(57) A method and apparatus for use as a high-power accelerator is described for which a charged particle beam is confined to an orbit and accelerated through a wide range of energies. A plurality of substantially identical fixed field magnet assemblies with fractal geometry allows to achieve such a confinement and control the shape and distance between consecutive turns of the beam in the accelerator. Each assembly includes a set of magnets for which a strength of a magnetic field varies non-linearly along a radial and azimuthal direction and achieves isochronous condition in a strong focusing regime. Example of magnet configurations relying on the fractal geometry and designed to fulfill the above-mentioned conditions are disclosed.

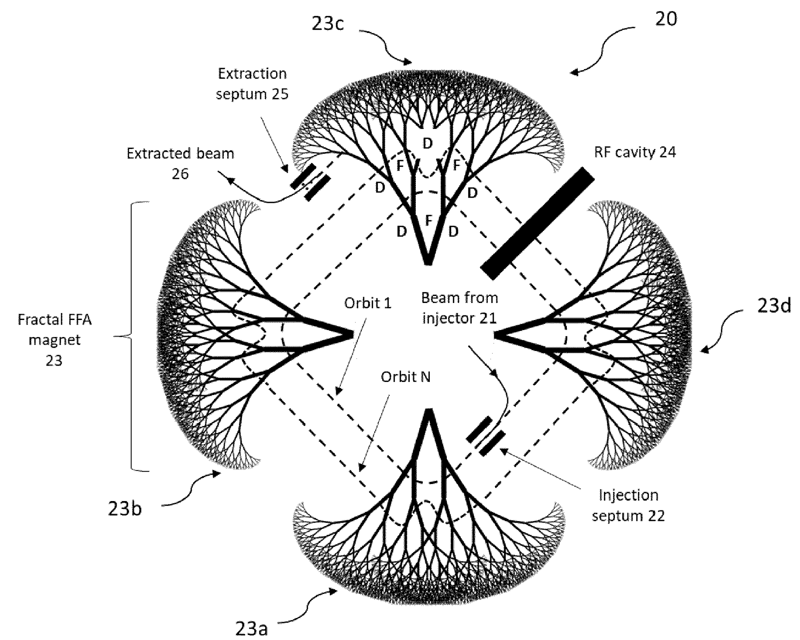

FIG. 2

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Description

Technical domain

[0001] The present invention concerns particle accelerator systems and especially, but not exclusively, power amplifiers producing high-current and high-energy beams at the megawatt (MW) level and beyond.

Related art

[0002] Nowadays, a growing number of applications such as medical radioisotopes, energy amplifiers and neutrino factories rely on particle accelerators producing high power beams. The two most common accelerator designs for producing high power beams are linacs and cyclotrons. Cyclotrons are more advantageous given that their footprint is lower than linacs and given their better energy efficiency. But cyclotrons are designed to operate in a Continuous Wave (CW) mode by continuously injecting the beam bunches which are accelerated in an isochronous regime to the extraction device. This mode of operation requires a rapid increase of the magnetic field with the radius of the beam which leads to the loss of vertical focusing and to the reduced orbit separation at extraction. The ratio of the beam size to the orbit separation at extraction determines the maximum beam that can be extracted with low losses and therefore the maximum achievable power from the cyclotron accelerator. Another limitation is that cyclotrons struggle to achieve energies beyond the GeV level due to the weak focusing and isochronism problem.

[0003] Therefore, there is a need for a particle accelerator that can overcome the intensity and energy limitations of cyclotrons and thus enabling high beam powers while maintaining the compactness of circular accelerators.

[0004] The background works listed in the section "References" of this disclosure provide additional scientific insight and may be useful to better understand the invention.

Short disclosure of the invention

[0005] Applicant has identified a need for a design of a strong focusing isochronous fixed field accelerator (FFA) enabling enough turn separation to extract the highest possible beam currents. Strong focusing allows the device to reach the highest energies beyond the cyclotrons reach (typically ~ 1 GeV for protons) and to confine the beam bunches to smaller sizes. The isochronous regime enables the continuous injection of bunches into the ring and allows to rapidly accelerate the beam in order to overcome resonance crossing issues which might lead to beam losses and unavoidable interlocks of the machine. Fixed field magnets were chosen because such magnets are easier to operate, and allow the use of superconducting magnets, which reach higher magnetic field strength (thus controlling the orbits of more energetic particles in smaller spaces). These approaches provide an accelerator that is more compact in size. The proposed design also provides a single turn extraction, no stripper at extraction, and less activation problems. A new degree of freedom is introduced in the design of the magnet, which is based on the fractal geometry. This enables to enhance the turn separation and to reduce the beam size at extraction compared to state-of-the-art fixed field accelerator concepts.

[0006] A system according to the invention comprises:

- a fixed field charged particle accelerator comprising
  an accelerating RF cavity; and
- a plurality of substantially identical fixed field magnets, arranged in a ring, wherein the fixed field magnet comprises alternating gradient focusing structures (Focusing-Defocusing, FD),

  wherein the F-magnet and D-magnets generate a guiding magnetic field which varies non-linearly with the radius, wherein the alternating gradient focusing structure is split into self-similar structures at higher radii.

[0007] The fixed field charged particle accelerator can be a non-scaling fixed field charged particle accelerator.

[0008] One or several of the following provisions, taken alone or in combination, can further be implemented:

- the crossing speed of betatron resonances can be controlled;
- all beams of the same charged particle type within the first range of energies have a same revolution frequency;
- the system further comprises an injection septum disposed along the first closed orbit and an extraction septum disposed along the last closed orbit;
- the turn separation at extraction is enhanced by lowering the gradient of the average magnetic field and enhancing the ratio of the magnetic field reversal (FD ratio) at the extraction region;
- the beam of charged particles is a beam of protons and the first range of energies for each proton is from about 75 million electron volts (MeV) to about 1775 MeV;

- a ratio between the maximum and minimum momentum of the charged particles is 6 or more;
- the system is configured such that the charged particles circulate in bunches, a radial distance between neighboring bunches being controlled by the fractal geometry of the magnet;
- in the latter case, the radial distance between neighboring bunches is possibly controlled by adjusting the fractal geometry of the magnet;
- the magnets are made of coils arranged to create desired azimuthal and radial field variations, wherein the desired radial field variation is obtained by tilting pairs of coils arranged symmetrically with respect to a first plane, and wherein the desired azimuthal variations of the magnetic field are achieved by configuring the location and width of the coils in the azimuthal direction such as the current flow is clockwise/counter-clockwise to produce the field pointing upwards/downwards. In an exemplary embodiment, a system for use as a compact high power ion accelerator includes a fixed field alternating gradient accelerator including a set of four arc sections connected to each other by means of four straight sections: the arc section can include one or several magnets with fractal geometry and is configured to rotate the charged particle by 90 degrees within a first plane. The magnetic field produced by the FFA magnets is perpendicular to the first plane and varies non-linearly along a radial direction from the center of the ring. The straight sections of the accelerator can include an injection septum to receive the injected beam of particles, an RF cavity and an extraction septum configured to eject the high energy particles. The magnet can be made superconducting or normal-conducting.

[0009] Still other aspects, features, and advantages are readily apparent from the following detailed description, simply by illustrating a number of particular embodiments and implementations, including the best approach for carrying out the invention. Other embodiments are also capable of other and different features and advantages, and its several details can be modified in various obvious respects, all without departing from the spirit and scope of the invention. Accordingly, the drawings and description are to be regarded as illustrative in nature, and not as restrictive.

Short description of the drawings

[0010] Embodiments are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings in which like reference numerals refer to similar elements and in which:

FIG. 1A is a block diagram that illustrates an orbital plane of an example scaling fixed field alternating gradient charged particle accelerator;

FIG. 1B is a block diagram that illustrates an orbital plane of an example cyclotron charged particle accelerator;

FIG. 2 is a block diagram that illustrates an orbital plane of an example fixed field alternating gradient accelerator with fractal magnet geometry;

FIG. 3A is a block diagram that illustrates an orbital plane of an example FFA triplet magnet with Defocusing-Focusing-Defocusing (DFD) structure;

FIG. 3B is a block diagram that illustrates an orbital plane of an example FFA magnet with fractal geometry that achieves non-linear magnetic field increase with the radius along with radial-dependent focusing structure that enables to enhance the turn separation at extraction and accelerate a proton beam in an isochronous regime from 75 MeV to 1775 MeV;

FIG. 3C shows the closed orbit trajectories in one magnet assembly by protons of kinetic energy from 75 MeV to 1775 MeV, according to an embodiment;

FIG. 3D shows magnetic field strength experienced along the orbit portion in one magnet assembly by protons of kinetic energy from 75 MeV to 1775 MeV, according to an embodiment;

FIG. 4 is a block diagram that illustrates another example of an orbital plane FFA with fractal magnet geometry where the F structures split into self-similar FDF structures at higher and higher radii;

FIG. 5A and 5B is a block diagram that illustrates an example of coils arrangement to generate the radial field increase of the magnetic field and create the radial-dependent alternating gradient focusing;

FIG. 6A is a block diagram that illustrates an example mid-plane magnetic field with coils arrangements corresponding to FIG. 5A and 5B;

FIG. 6B is a block diagram that illustrates another example mid-plane magnetic field with coils arrangements moved closer to each other;

FIG. 7A is a block diagram that illustrates the horizontal beam stability diagram as a function of the average field index and the FD ratio of the magnet, along with the extraction path; and

FIG. 7B is a block diagram that illustrates the vertical beam stability diagram as a function of the average field index and the FD ratio of the magnet, along with the extraction path.

Detailed description

[0011] A method and apparatus are described for a particle accelerator with fractal magnetic field geometry. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to avoid unnecessarily obscuring the present invention.

[0012] Notwithstanding that the numerical ranges and parameters setting forth the broad scope are approximations, the numerical values set forth in specific non-limiting examples are reported as precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements at the time of this writing. Furthermore, unless otherwise clear from the context, a numerical value presented herein has an implied precision given by the least significant digit. Thus, a value 1.1 implies a value from 1.05 to 1.15. The term "about" is used to indicate a broader range centered on the given value, and unless otherwise clear from the context implies a broader range around the least significant digit, such as "about 1.1" implies a range from 1.0 to 1.2. If the least significant digit is unclear, then the term "about" implies a factor of two, e.g., "about X" implies a value in the range from 0.5X to 2X, for example, about 100 implies a value in a range from 50 to 200. Moreover, all ranges disclosed herein are to be understood to encompass any and all sub-ranges subsumed therein. For example, a range of "less than 10" can include any and all sub-ranges between (and including) the minimum value of zero and the maximum value of 10, that is, any and all sub-ranges having a minimum value of equal to or greater than zero and a maximum value of equal to or less than 10, e.g., 1 to 4.

[0013] Some embodiments of the invention are described below in the context of accelerating protons from 75 million electron volts (MeV) to 1775 MeV. The kinetic energy of the ion is expressed in electron volts, the amount of kinetic energy imparted to one electron by a voltage difference of one volt. However, the invention is not limited to this context. In other embodiments, other magnets of greater or lesser strength are used, allowing other ions of greater or lesser charges to be maintained up to higher or lower energies in accelerators of the same or different size.

[0014] A Fixed-Field alternating gradient Accelerator (FFA) is a circular particle accelerator on which development was started in the early 1950s, and that can be characterized by its time-independent magnetic fields (fixed-field, like in a cyclotron) and the use of strong focusing (alternating gradient, like in a synchrotron). As particles increase in kinetic energy, the radius of their orbit increases until the maximum energy is attained, and the particles exit the device. Because the orbits do not overlap, a continuous stream of particles can be accelerated. The radial increase of the magnetic field, and thus the increase of the gradient, allows the device to control the change of the particle revolution frequency with the energy. The magnet can be made superconducting or normal-conducting.

[0015] This concept is demonstrated in FIG. 1A. FIG. 1A is a block diagram that illustrates an orbital plane of an example fixed field alternating gradient charged particle accelerator. The curved trapezoidal figures are the footprint of the fixed field magnets 13, i.e., magnets that do not change their magnetic field strength with time. The magnetic field is directed perpendicular to the page and into the page for a positively charged ion, such as a proton, to move clockwise (or a negatively charged ion to move counterclockwise). In these embodiments, the magnets 13 serve only to maintain the particles in a focused beam that is forced to circulate in 360 degree turns. Because the magnets 13 are separated in space, the particles follow a straight path between magnets and then are turned, focused (F) and defocused (D) by encountering the spatially alternating magnetic field (in the pattern DFD) at each magnet 13, then again go straight as they leave the field of the magnet 13. The particle thus experiences an alternating gradient magnetic field, hence the name. The magnets have greater strength at greater radius so that they can turn a greater energy particle the same angular amount. In a cyclotron as shown in FIG. 1B, there is no alternation of the gradient and the magnetic field increases radially in order to keep the revolution time of the particles constant. Thus, a cyclotron is a weak focusing accelerator in comparison to a FFA accelerator.

[0016] In FIG. 1A, the particles are accelerated in a radio frequency cavity (RF cavity 12) by the application of an electric field timed to attract the charged particles as they approach and to repel the charged particles as they recede from the RF cavity. After each acceleration, the particle has increased its momentum (and hence its energy) and thus takes more distance to turn the 360 degrees. Thus the next orbit 14 is further from the center of the orbits. Each successive orbit is further out as the kinetic energy of the ions increases. Thus the FFA accelerator is designed to output particles of only a certain energy at the maximum radius, represented by the extraction ray.

1. Overview

[0017] FIG. 2 is a block diagram that illustrates an orbital (X,Y) plane, also called horizontal plane, of an example fixed field accelerator with fractal magnet geometry 20, according to an embodiment. This system 20 includes a charged particle linear accelerator module, such as RF cavity 24, and four fixed field magnet assemblies 23a, 23b, 23c and 23d either referenced as assembly 23 in an exemplary embodiment.

[0018] The fixed field magnet assembly 23 is configured to control the orbits of the pulse in the device by turning a moving charged particle 90 degrees within a first plane (the X,Y orbital plane of FIG. 2).

[0019] Each assembly 23 includes FFA shaped magnets for which a strength Bz on the X,Y plane of a magnetic field perpendicular to the X,Y plane varies non-linearly along a radial direction from the reference point, which is not a dipole magnet; Such a magnetic field is split into self-similar structures at higher and higher radii. The iterated function to generate such a fractal field map is also shown whereby the alternating gradient focusing structure is split into self-similar structures to enable stronger focusing for more energetic particles. Thus, assembly 23 may resemble a tree-like fractal. For instance, when the beam accelerates from orbit 1 to orbit N, the focusing structure develops from a DFD (D for Defocusing and F for Focusing) to a DFDFD. This generates more wiggled orbits with modified path lengths.

[0020] FIG.3B is a block diagram that illustrates an orbital plane of an isochronous FFA with fractal magnet geometry, according to another embodiment. In this embodiment, the orbits are accelerated from 75 MeV to 1775 MeV such that the average magnetic field along each orbit is chosen to maintain a constant revolution frequency.
In order to enhance the turn separation at extraction (see FIG.3C), the beam is first focused by enhancing the splitting of the focusing structures D4DFD4DF DFDFDFDFDFDFDFD which increases the alternating gradient focusing effect. Then, the ratio of negative field to positive field is adjusted radially in order to pack together the closed orbits in the central region and create more separation at extraction. For instance, an orbit separation of 7cm at least can be achieved for the last couple of turns. The shape of the magnetic field allowing this is shown in FIG. 3D. The increased variation of the field acts on the average trajectory of the beam but also modifies the focusing effect.

[0021] According to another embodiment, the fractal splitting of the magnetic field can evolve in a random way as seen in FIG.4. This can be utilized in order to enhance the turn separation at the location of the extraction device only. In this example, the focusing part of the structure in Orbit 1 splits into an FDF structure. The focusing part of the latter in Orbit 2 is subsequently split into another FDF structure.

2. Example Embodiments

[0022] Various example embodiments are described herein and their performances are simulated. One of the major concerns in ring accelerators is the crossing of the transverse resonances. The latter can lead to losses of the majority of ions in the beam. Thus, it is desirable to come up with a ring accelerator concept in which the crossing of the transverse resonances is very rapid to overcome its effect. Besides, a key requirement to extract the highest possible currents is to maintain the smallest beam sizes at extraction. This can be achieved by avoiding the loss of focusing during acceleration (as is the case in linear non-scaling FFA).

[0023] FFAs with fractal magnet geometry have the property that their focusing can be continuously adjusted by creating iterated functions at higher and higher radii that splits the initial focusing structure (i.e., at lower radii) into self-similar structures at higher radii.

[0024] In one embodiment, the vertical component of the field of the magnet is expressed as in Equation 1.

$$B(R,\theta) = (B_0 + B_1 R + B_2 R^2 + B_3 R^3 + B_4 R^4) \times F(R,\theta) \qquad (1)$$

where B is the vertical (Z direction) component of the magnetic field in the median plane of the accelerator, R is the radial coordinate with respect to the center of the orbits, B_0 the reference field at $R = R_0$ and $F(R,\theta)$ is a fringe field factor (also called a flutter function) that describes the azimuthal variation of the field of the magnet and which is not separable in radial and azimuthal coordinates. For a N sector accelerator, it is sufficient to define 1/Nth of the entire orbit, which is $2\pi/N$ radians of a full 2π orbit. In one embodiment, the flutter function is based on the Enge model and is given as a piecewise function of the radius. Equation 2.

$$F(R,\theta) = \frac{1}{1+e^{P_1(R,\theta)}} \times \frac{1}{1+e^{P_2(R,\theta)}} \qquad (2)$$

Where the polynomials *P* describe the fringe field falloff at the edge of the magnet; and, the subscript 1 indicates the entrance of the magnet, and the subscript 2 indicates the exit of the magnet. In this embodiment, the polynomials are given by Equations 3 and 4.

$$P_1(R,\theta) = C_0 + C_1 \times (\theta - \theta_1) + C_2 \times (\theta - \theta_1)^2 + C_3 \times (\theta - \theta_1)^3;\ \theta_1 > 0 \qquad (3)$$

$$P_2(R,\theta) = C_0 + C_1 \times (\theta + \theta_2) + C_2 \times (\theta + \theta_2)^2 + C_3 \times (\theta + \theta_2)^3;\ \theta_2 > 0 \qquad (4)$$

The azimuthal spread, given by θ_1 and θ_1 can be varied to control the positioning of the magnets and the overall accelerator size, e.g., by maximizing a packing factor. Note that both polynomials have the same coefficients C_i in order to impose symmetry on the fringe fields in this embodiment. In other embodiments the symmetry is not required; and, the coefficients may be different or change with the radius. At larger radii, harmonics are introduced to create more alternating gradient focusing structures and generate the fractal shape of the magnet.

[0025] The magnetic field required obeys Maxwell equations and its amplitude depends on the footprint of the accelerator, the injection/extraction energies i.e., the momentum multiplication factor, as well as the amplitude of field reversal. The use of superconducting magnet technology ensures that a wide range of optics can be explored. A general approach to handle the design generation and optimization is of interest. Since the magnets are made of coils arranged to create the desired azimuthal and radial field variations, the magnetic field calculations can be performed by integrating the Biot-Savart law initially. A simple example relying on such a calculation is shown in FIG. 6A. The coils arrangement enabling this are displayed in FIG. 5A and 5B. Here, each loop consists of two coils tilted symmetrically with respect to the XY plane (median plane) such as they come closer together towards larger radii. This produces the observed field increase in X direction. To produce the field pointing upwards/downwards, the current flow is clockwise/counter-clockwise. The arrangement can be iterated by breaking the coils into self-similar structures at higher radii and applying the superposition principle. Furthermore, optimizing the location of the coils can have major effects on the fringing field of the structure as shown in FIG 6B where the coils are moved closer together in comparison with FIG. 6A.

[0026] The effects of such fields on the trajectories of the ions in the accelerator can be simulated, e.g., with the ion ray-tracing code ZGOUBI, available at subfolder folder *zgoubi* of folder *projects* at world wide web domain *sourceforge* of super-domain *net*.

[0027] Step 1, Generate a median plane field map for a given lattice (a lattice refers to an accelerator with a specific configuration): the lattice is characterized by the flutter function *F* that is chosen to have a first stable lattice (e.g. FIG. 3A), the field increase with the radius given by Equation 1, the width of the magnet, as well as the magnetic field B_0 defined at $R = R_0$ which determines the lower radius of the accelerator. The latter is optimized in order to provide enough space to place other elements such as the injection elements and the beam diagnostics. The flutter function F is then modified in a way to represent the fractal geometry of the magnet and thus becomes Radial-dependent. An example of such flutter function enabling to generate the fractal structure shown in FIG. 3B for an N-sector machine is expressed as follows:

$$F(R,\theta) = 1 + a_1 \times \cos(N\theta) + a_2(R) \times \cos(4N\theta) + a_3(R) \times \cos(8N\theta) + a_4(R) \times \cos(16N\theta) + \ldots$$

where the radial-dependent coefficients are defined as follows:

$$a_2(R) = 0, \text{ if } R \le R_{20}$$

$$a_2(R) = \left(\frac{R}{R_{20}} - 1\right) \times a_{20}, \text{ if } R_{20} \le R \le R_{20} + \Delta R$$

$$a_2(R) = (\frac{\Delta R}{R_{20}}) \times a_{20}, \text{ if } R_{20} + \Delta R \leq R$$

And where R_{20}, ΔR and a_{20} are constants that define the minimum radius at which the harmonic component appears, the radial extent allowing the amplitude of the harmonic to change radially, and the scaling factor defining the amplitude of such a variation.

The same applies to all other components, i.e., $a_3(R)$, $a_4(R)$, etc. Enhancing the field variations by introducing higher order harmonics with positive and negative fields enhances the scalloping of the orbit, and also enables to increase the Alternating Gradient focusing.

[0028] Step 2. Use the tracking code ZGOUBI to track the particles in the field map. Accommodating the Maxwell equations allows to determine the magnetic field components out of the median plane.

[0029] Step 3. Use a fitting method to find the closed orbits for different energies and assess the level of isochronism achieved. If the revolution frequency changes with the energy by more than 1%, the average field increase is adjusted for both the Focusing and the Defocusing magnets as well as the shape of the flutter function. This is done gradually for larger and larger radii adjusting the amplitude of the flutter variation for a given radial span (e.g. , a_{20} for $R_{20} \leq R \leq R_{20} + \Delta R$)

[0030] Step 4. Ensure the stability of the particle trajectories in the transverse plane. For this, one constructs the one-turn transfer map of the lattice. This is achieved by tracking particles with small displacements from each closed orbit, e.g., from each different particle energy. The number of betatron oscillations per turn is thus computed for each energy to determine the level of focusing achieved. Based on the scheme described in FIG. 3B, the number of oscillations per turn can Increase by a factor of four from low energy to high energy. This results from the enhancement of the Alternating Gradient focusing is such a scheme.

[0031] Step 5. Optimize the distance between consecutive turns at the extraction region by locally reducing the field strength k (k = R/B dB/dR which measures the increase of the magnetic field with the radius) and enhancing the FD ratio (ratio between the focusing and defocusing field amplitudes). An example of an extraction path is shown in FIG. 7A and 7B where the focusing remains unchanged in the horizontal plane and is increased in the vertical one (the FD ratio adjustment at extraction introduces a new degree of freedom that is not possible in cyclotrons where the common practice is to reduce the field strength for the last few turns only leading to the weakening of the horizontal beam focusing).

4. Alternations, deviations and modifications

[0032] In the foregoing specification, the invention has been described with reference to specific embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the invention. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. Throughout this specification and the claims, unless the context requires otherwise, the word "comprise" and its variations, such as "comprises" and "comprising," will be understood to imply the inclusion of a stated item, element or step or group of items, elements or steps but not the exclusion of any other item, element or step or group of items, elements or steps. Furthermore, the indefinite article "a" or "an" is meant to indicate one or more of the item, element or step modified by the article. As used herein, unless otherwise clear from the context, a value is "about" another value if it is within a factor of two (twice or half) of the other value. While example ranges are given, unless otherwise clear from the context, any contained ranges are also intended in various embodiments. Thus, a range from 0 to 10 includes the range 1 to 4 in some embodiments.

[0033] The merit of the field maps is that, once the magnets are built, the simulated fieldmaps can be replaced with the measured ones to yield a realistic representation of the accelerator model.

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[0034]

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Claims

1. 1. A system (20) comprising:

- a fixed field charged particle accelerator comprising
- an accelerating RF cavity (12, 24); and
- a plurality of substantially identical fixed field magnets (13, 23), arranged in a ring, wherein the fixed field magnet comprises alternating gradient focusing structures (Focusing-Defocusing, FD),

wherein the F-magnet and D-magnets generate a guiding magnetic field which varies non-linearly with the radius, wherein the alternating gradient focusing structure is split into self-similar structures at higher radii.

2. A system (20) as recited in claim 1, wherein all beams of the same charged particle type within the first range of energies have a same revolution frequency.

3. A system (20) as recited in any one of the preceding claims, further comprising an injection septum disposed along the first closed orbit and an extraction septum disposed along the last closed orbit.

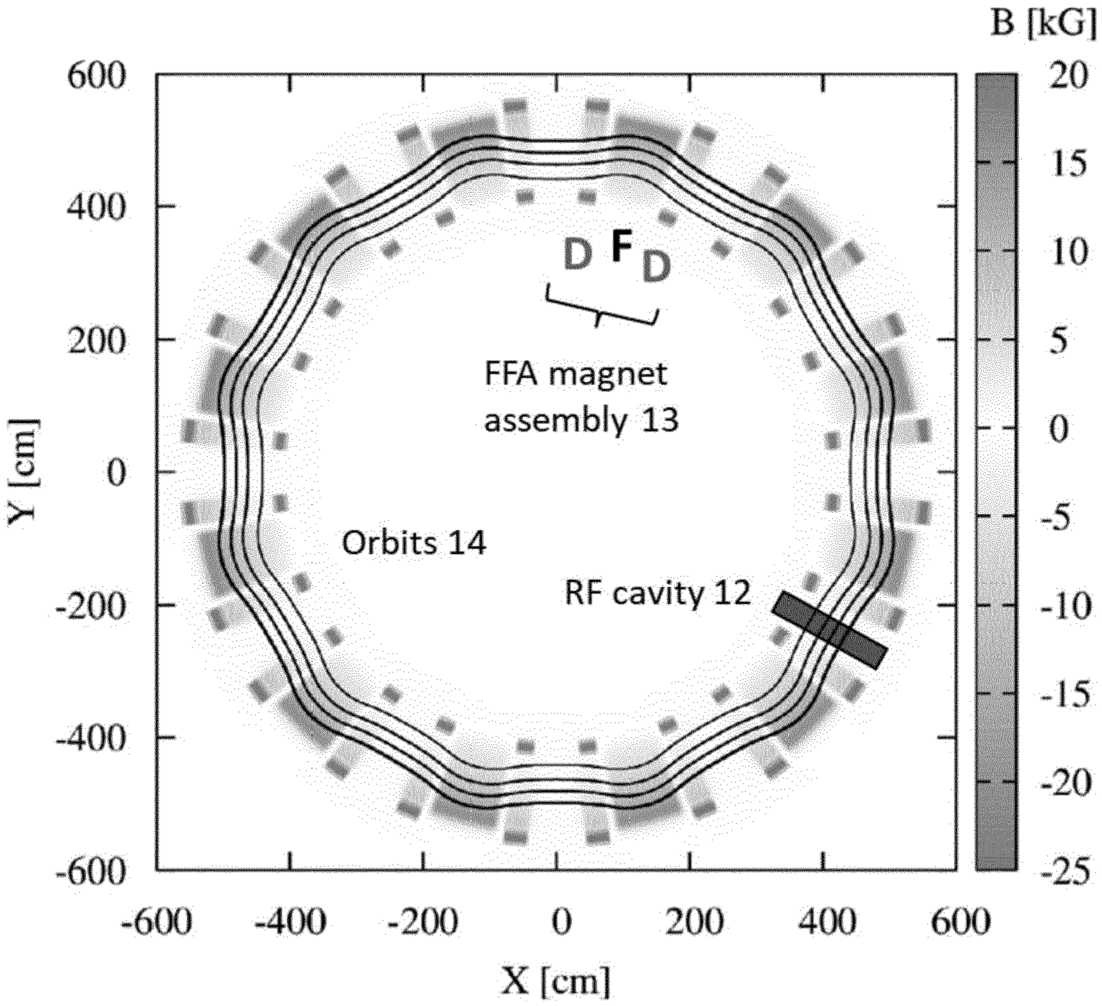
4. A system (20) as recited in the preceding claim, wherein the turn separation at extraction is enhanced by lowering the gradient of the average magnetic field and enhancing the ratio of the magnetic field reversal (FD ratio) at the extraction region.

5. A system (20) as recited in any one of the preceding claims, wherein the beam of charged particles is a beam of protons and the first range of energies for each proton is from about 75 million electron volts (MeV) to about 1775 MeV.

6. A system as recited in any one of the preceding claims, wherein a ratio between the maximum and minimum momentum of the charged particles is 6 or more.

7. A system as recited in any one of the preceding claims, configured such that the charged particles circulate in bunches, a radial distance between neighboring bunches being controlled by the fractal geometry of the magnet.

8. A system as recited in claim 2, wherein the magnets are made of coils arranged to create desired azimuthal and radial field variations, wherein the desired radial field variation is obtained by tilting pairs of coils arranged symmetrically with respect to a first plane, and wherein the desired azimuthal variations of the magnetic field are achieved by configuring the location and width of the coils in the azimuthal direction such as the current flow is clockwise/counter-clockwise to produce the field pointing upwards/downwards.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600
X [cm]
D
F
D
FFA magnet
assembly 13
Orbits 14
RF cavity 12

FIG. 1A

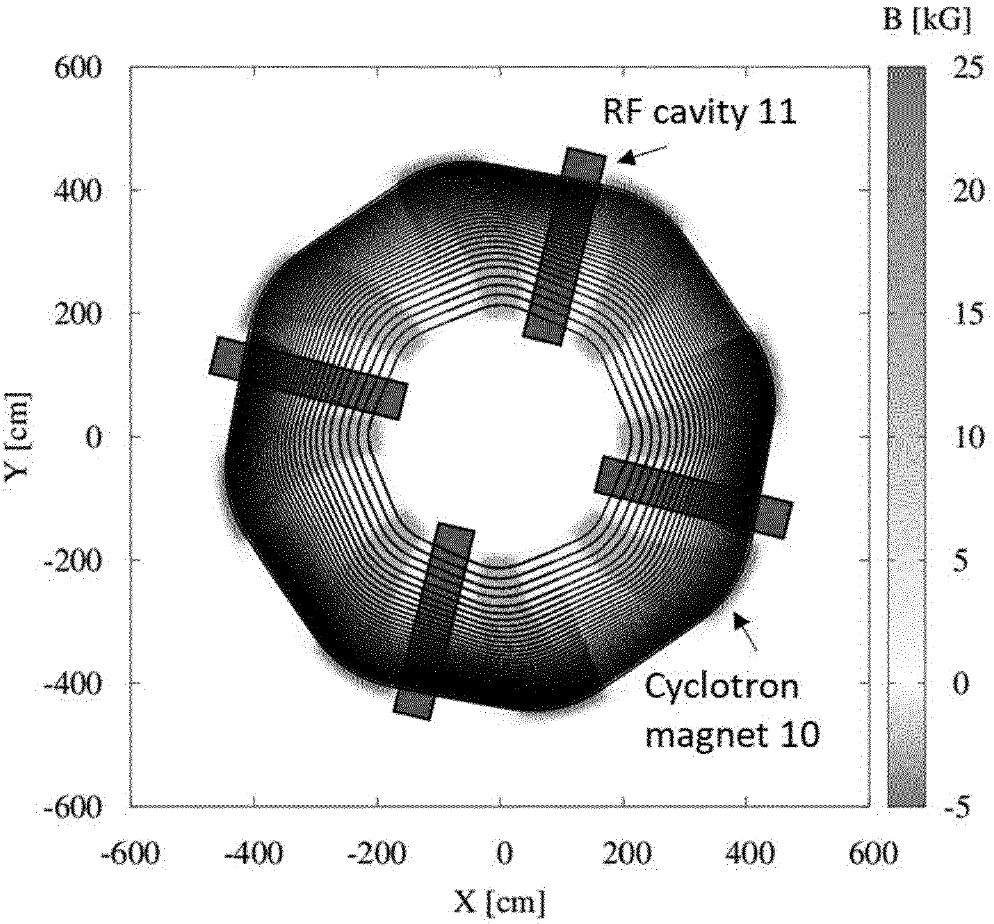

B [kG]
25
20
15
10
5
0
-5
600
400
200
0
-200
-400
-600
Y [cm]
-600
-400
-200
0
200
400
600
X [cm]
RF cavity 11
Cyclotron magnet 10

FIG. 1B

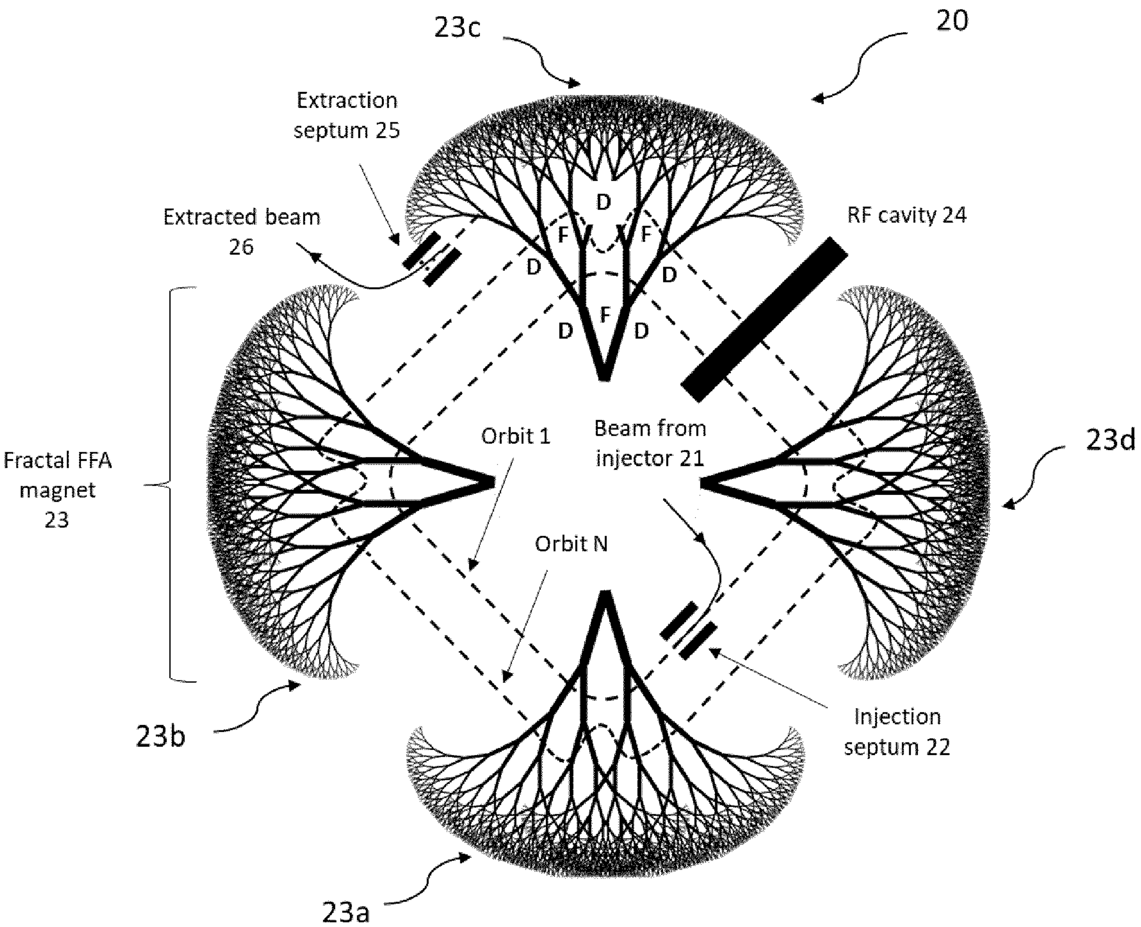

23c
20
Extraction
septum 25
Extracted beam
26
D
F
F
D
D
F
D
D
RF cavity 24
Fractal FFA
magnet
23
Orbit 1
Beam from
injector 21
23d
Orbit N
23b
Injection
septum 22
23a

FIG. 2

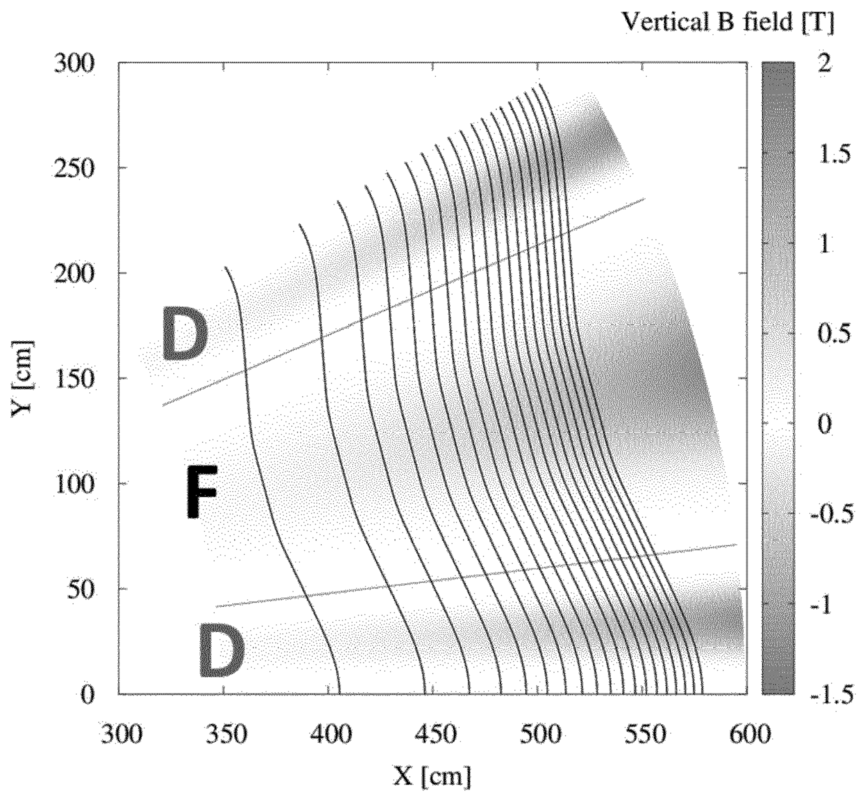

Vertical B field [T]
2
1.5
1
0.5
0
-0.5
-1
-1.5
300
250
200
150
100
50
0
Y [cm]
D
F
D
300
350
400
450
500
550
600
X [cm]

FIG. 3A

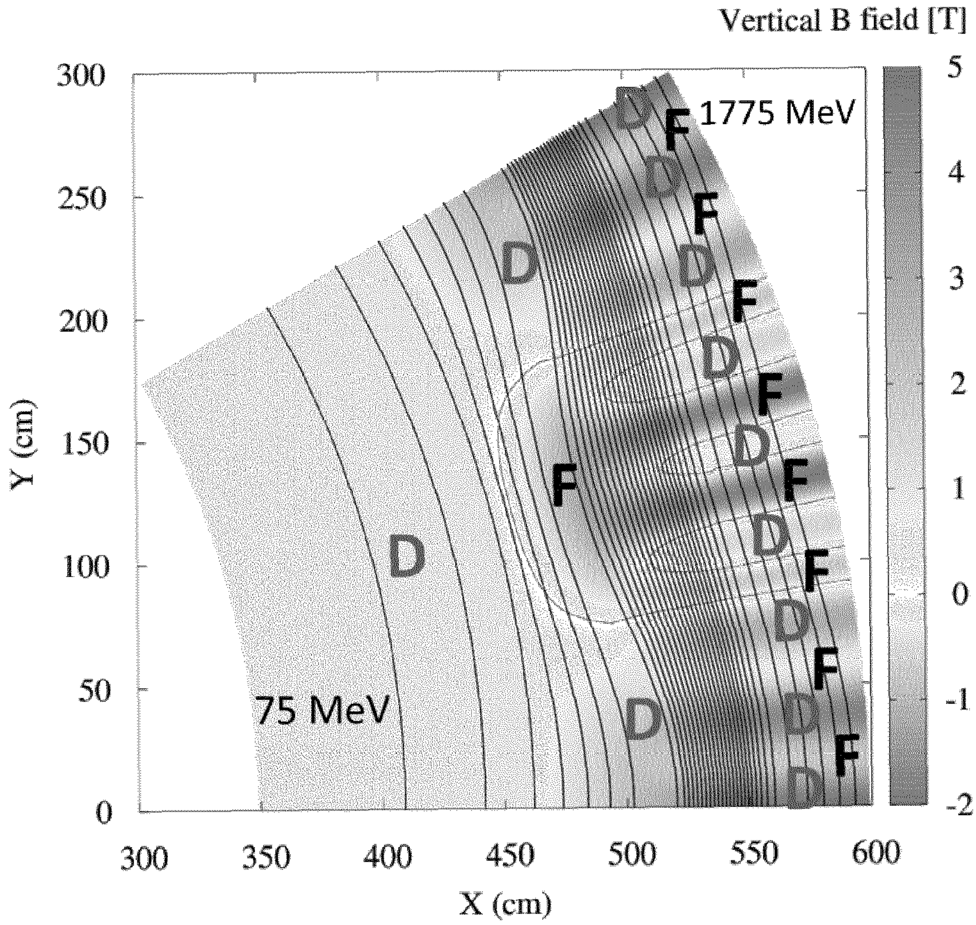

Vertical B field [T]
5
4
3
2
1
0
-1
-2
300
250
200
150
100
50
0
Y (cm)
300
350
400
450
500
550
600
X (cm)
1775 MeV
75 MeV
D
F

FIG. 3B

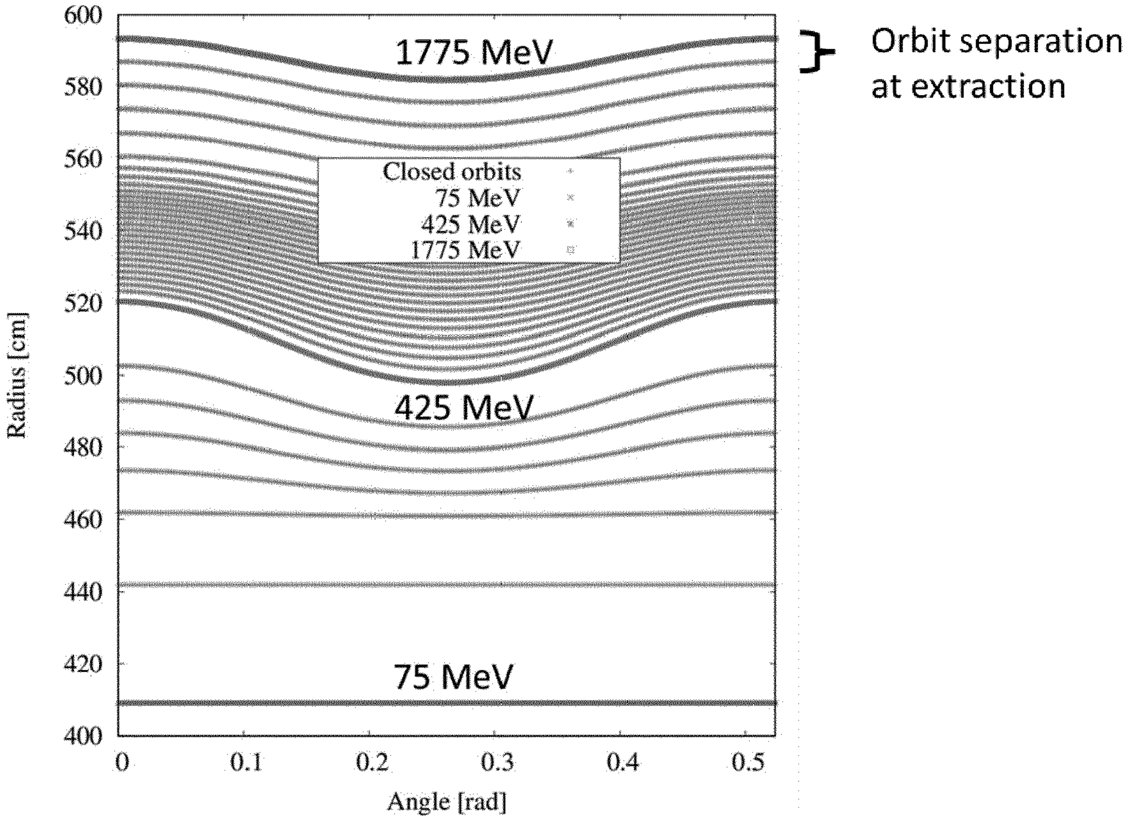

600
580
560
540
520
500
480
460
440
420
400
Radius [cm]
0
0.1
0.2
0.3
0.4
0.5
Angle [rad]
1775 MeV
425 MeV
75 MeV
Closed orbits
75 MeV
425 MeV
1775 MeV
Orbit separation at extraction

FIG. 3C

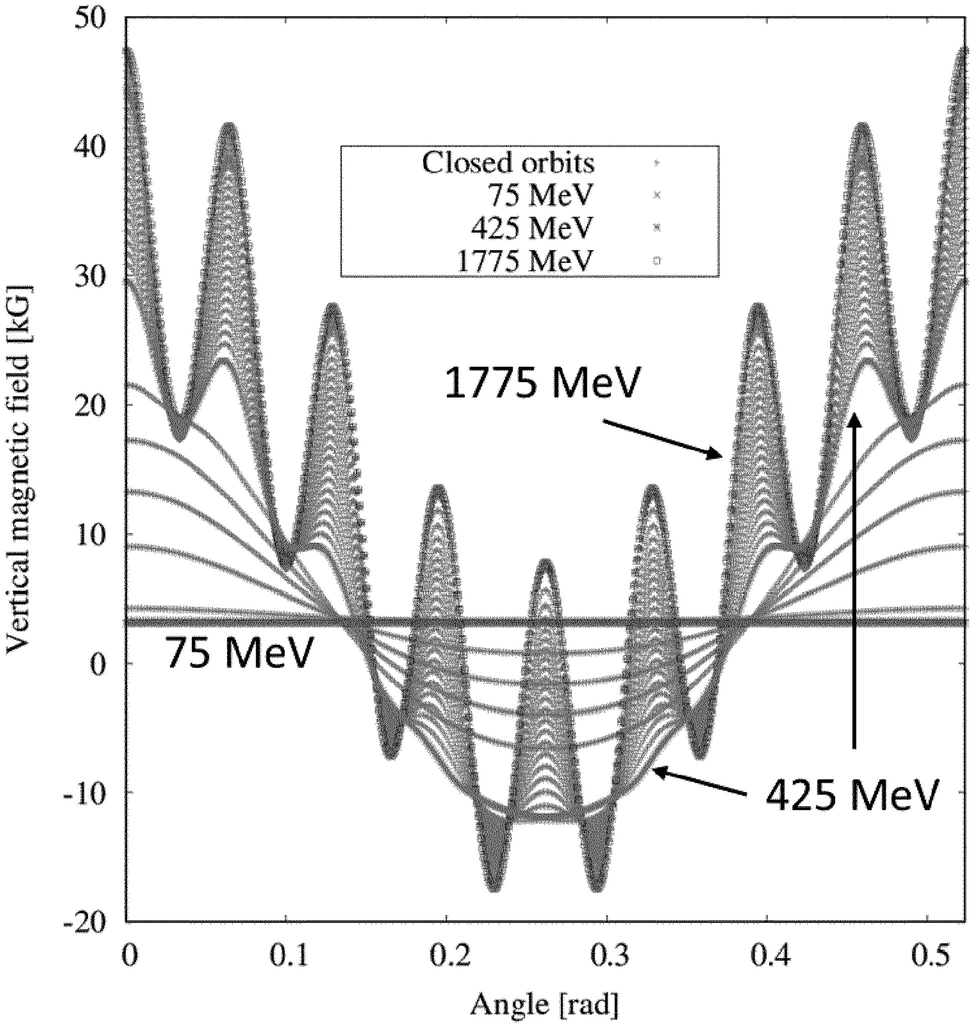

50
40
30
20
10
0
-10
-20
Vertical magnetic field [kG]
0
0.1
0.2
0.3
0.4
0.5
Angle [rad]
Closed orbits
75 MeV
425 MeV
1775 MeV
1775 MeV
75 MeV
425 MeV

FIG. 3D

Iterated function for such a fractal:

Orbit 1: **DFD**

Orbit 2: **DFDFD**

Orbit 3: **DFDFDFD**

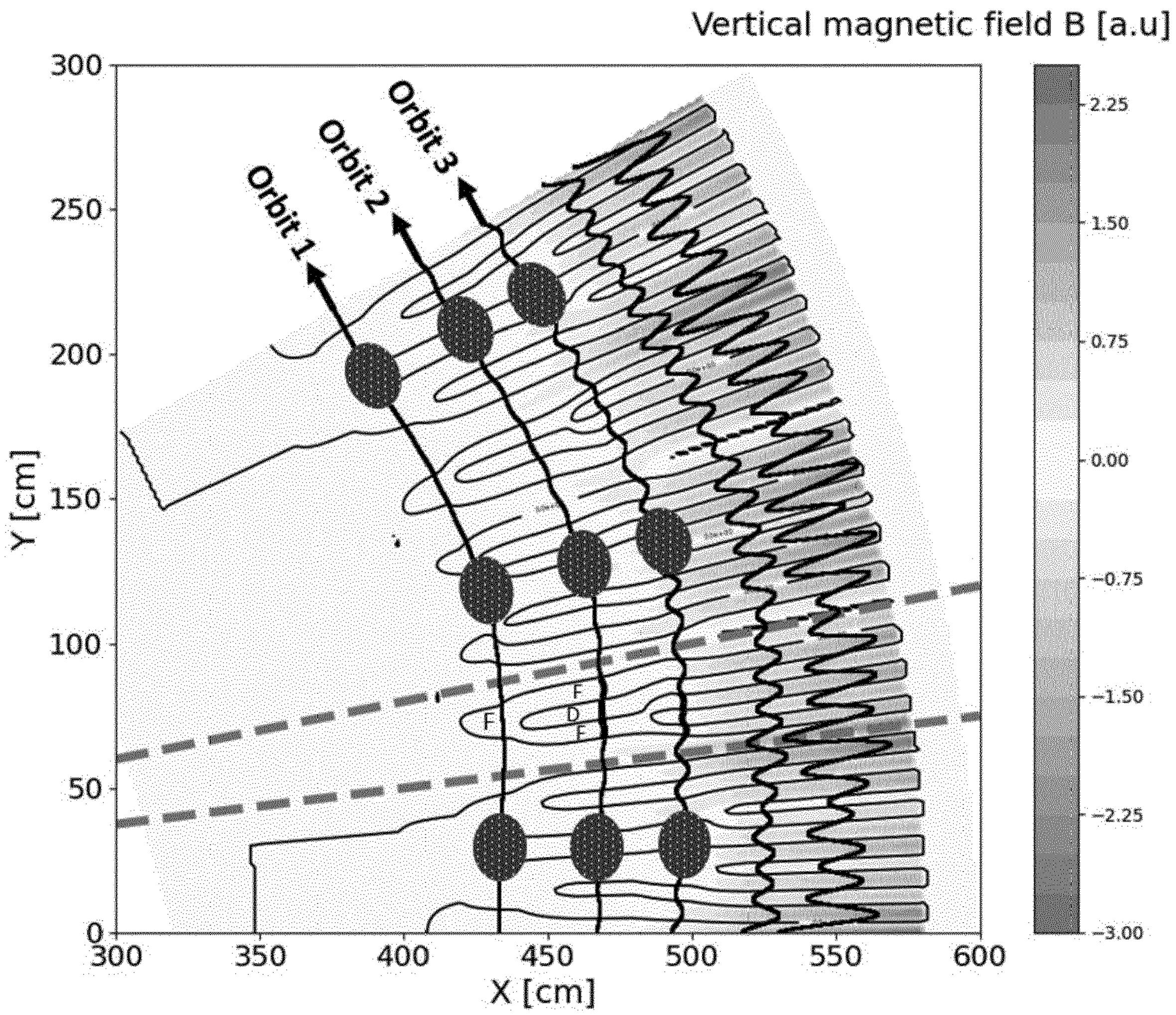
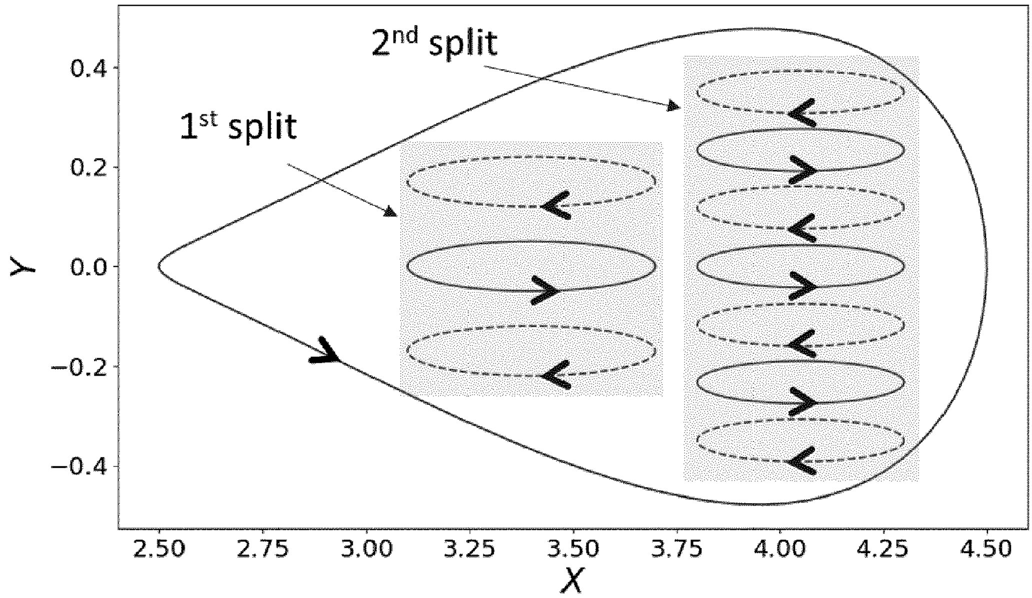
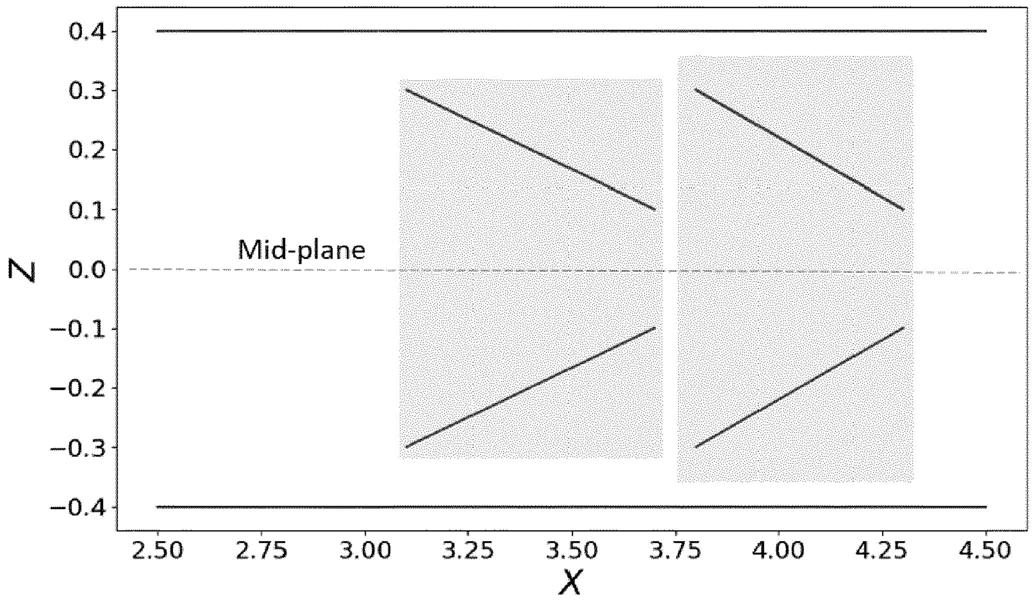


FIG.4



2nd split
1st split
0.4
0.2
0.0
−0.2
−0.4
Y
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
X

FIG. 5A



Mid-plane
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
Z
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
X

FIG. 5B

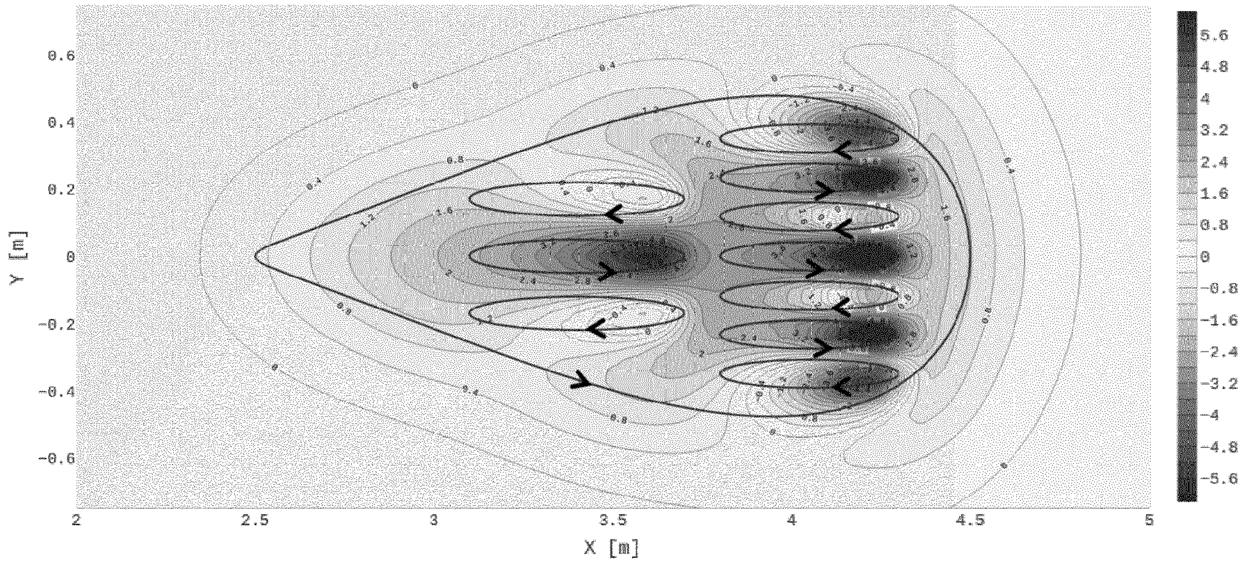

Y [m]
X [m]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
2
2.5
3
3.5
4
4.5
5
5.6
4.8
4
3.2
2.4
1.6
0.8
0
-0.8
-1.6
-2.4
-3.2
-4
-4.8
-5.6

FIG. 6A

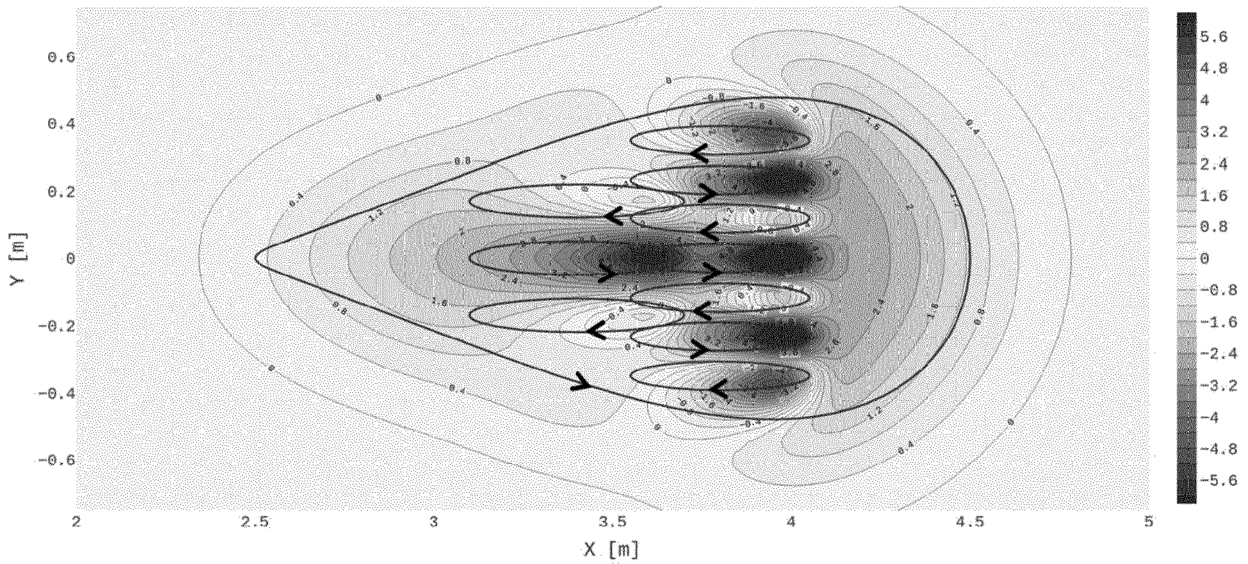

Y [m]
X [m]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
2
2.5
3
3.5
4
4.5
5
5.6
4.8
4
3.2
2.4
1.6
0.8
0
-0.8
-1.6
-2.4
-3.2
-4
-4.8
-5.6

FIG. 6B

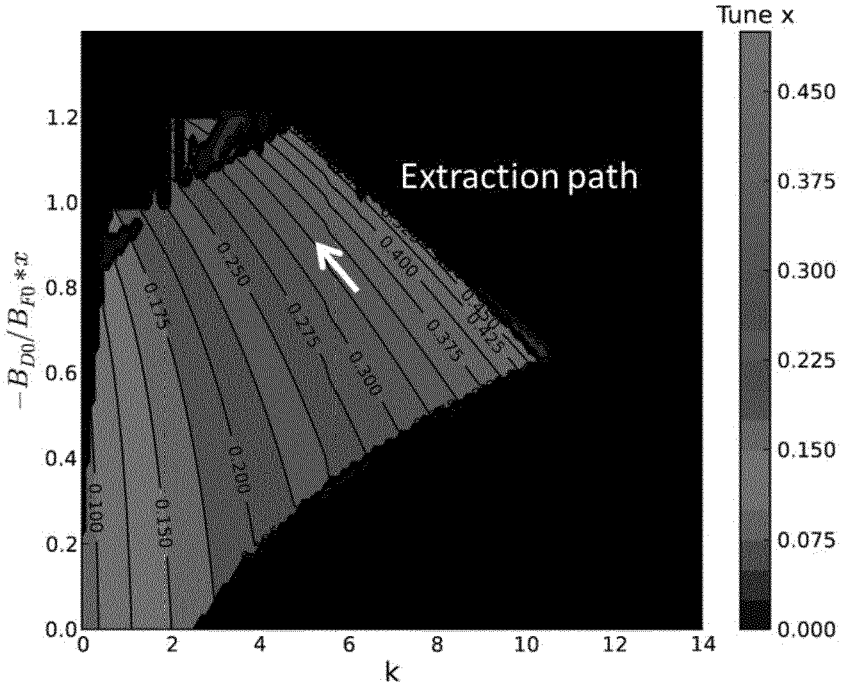

Tune x
Extraction path
k
$-B_{D0}/B_{F0}*x$
0.450
0.375
0.300
0.225
0.150
0.075
0.000

FIG. 7A

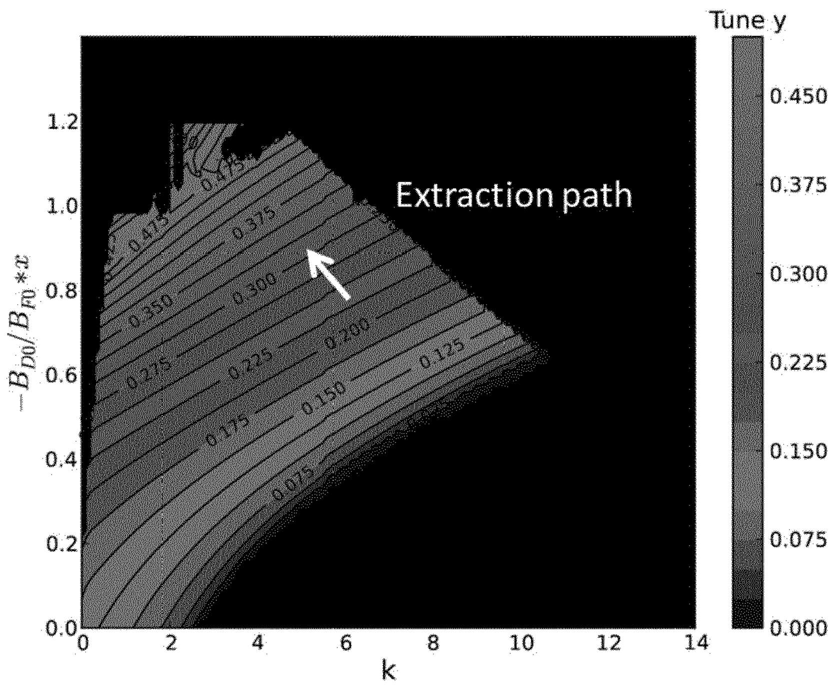

Tune y
Extraction path
k
$-B_{D0}/B_{F0}*x$
0.450
0.375
0.300
0.225
0.150
0.075
0.000

FIG. 7B

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EUROPEAN SEARCH REPORT

Application Number
EP 23 20 0620

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X A	CN 109 348 609 A (CHINA INST ATOMIC ENERGY) 15 February 2019 (2019-02-15) * figures 1-5 * * paragraph [0001] - paragraph [0080] * -----	1-6,8 7	INV. H05H13/08 H05H7/04
A	AIBA M ET AL: "The Magnet Design Study for the FFAG Accelerator", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, IEEE, USA, vol. 14, no. 2, 1 June 2004 (2004-06-01), pages 397-401, XP011117354, ISSN: 1051-8223, DOI: 10.1109/TASC.2004.829680 * figures 1,2,4-6 * * page 397, left-hand column, paragraph 1 - page 401, right-hand column, paragraph 5 * -----	1-8	
A	Johnstone C ET AL: "1 GeV CW nonscaling FFAG for ADS, and magnet parameters", , 20 May 2012 (2012-05-20), pages 1-5, XP093126988, Retrieved from the Internet: URL:https://www.osti.gov/servlets/purl/1049283 [retrieved on 2024-02-02] * figures 1-6 * * page 1, left-hand column, paragraph 1 - page 5, left-hand column, paragraph 2 * -----	1-8	TECHNICAL FIELDS SEARCHED (IPC) H05H

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	2 February 2024	Clemente, Gianluigi

CATEGORY OF CITED DOCUMENTS

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 109348609 A	15-02-2019	NONE	

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