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(54) **GRADIENT CORRECTOR FOR CYCLOTRON**

GRADIENTENKORREKTOR FÜR ZYKLOTRON

CORRECTEUR DE GRADIENT POUR CYCLOTRON

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Description**Field of the invention**

5 **[0001]** The present invention concerns cyclotrons. In particular, it concerns isochronous sector-focused cyclotrons having enhanced focusing of an extracted beam of energized charged particles.

Technical background

10 **[0002]** A cyclotron is a type of circular particle accelerator in which negatively or positively charged particles are accelerated outwards from the centre of the cyclotron along a spiral path up to energies of several MeV. Unless otherwise indicated, the term "cyclotron" is used in the following to refer to isochronous cyclotrons. Cyclotrons are used in various fields, for example in nuclear physics, in medical treatment such as proton-therapy, or in radio-pharmacy. In particular, cyclotrons can be used for producing short-lived positron-emitting isotopes suitable for PET imaging (positron emitting tomography) or for producing gamma-emitting isotopes, for example, Tc99m, for SPECT imaging (single photon emission computed tomography).

15 **[0003]** A cyclotron comprises several elements including an injection system, a radiofrequency (RF) accelerating system for accelerating the charged particles, a magnetic system for guiding the accelerated particles along a precise path, an extraction system for collecting the thus accelerated particles, and a vacuum system for creating and maintaining a vacuum in the cyclotron.

20 **[0004]** A particle beam constituted of charged ions is introduced into a gap at or near the center of the cyclotron by the injection system with a relatively low initial velocity. As illustrated in Fig. 3, this particle beam is sequentially and repetitively accelerated by the RF accelerating system and guided outwards along a spiral path comprised within the gap by the magnetic field generated by the magnetic system. When the particle beam reaches its target energy, it can be extracted from the cyclotron by the extraction system provided at a point of extraction, **PE**. This extraction system can comprise, for example, a stripper consisting of a thin sheet of graphite. For example, H⁻ ions passing through the stripper lose two electrons and become positive. Consequently, the curvature of their path in the magnetic field changes its sign, and the particle beam is thus led out of the cyclotron towards a target. Other extracting systems exist which are well known to the persons skilled in the art.

25 **[0005]** The magnetic system generates a magnetic field that guides and focuses the beam of charged particles along the spiral path until it is accelerated to its target energy. In the following, the terms "particles", "charged particles", and "ions" are used indifferently as synonyms. The magnetic field is generated in the gap defined between two magnet poles by two solenoid coils, **14**, wound around these poles. Magnet poles of cyclotrons are often divided into alternating hill sectors and valley sectors distributed around a central axis. The gap between two magnet poles is smaller at the hill sectors and the larger at the valley sectors. A strong magnetic field is thus created in the hill gap portions within the hill sectors and a weaker magnetic field is created in the valley gap portions within the valley sectors. Such azimuthal magnetic field variations provide radial and vertical focusing of the particle beam every time the particle beam reaches a hill gap portion. For this reason, such cyclotrons are sometimes referred to as sector-focusing cyclotrons. In some embodiments, a hill sector has a geometry of a circular sector similar to a slice of cake with a first and second lateral surfaces extending substantially radially towards the central axis, a generally curved peripheral surface, a central surface adjacent to the central axis, and an upper surface defining one side of a hill gap portion. The upper surface is delimited by a first and second lateral edges, a peripheral edge, and a central edge.

35 **[0006]** In practice, a particle beam has a cross sectional area. An objective of cyclotrons is to produce charged particle beams having a given energy which are as much focused as possible (i.e. having a small cross sectional area). The variations of the magnetic field created by the succession of hill sectors and valley sectors contributes to the focusing of the beam in a similar way as a light beam can be focused by lenses. Upon extraction of the particle beam out of the gap defined between two magnet poles, however, the particle beam crosses boundary regions where the magnetic field loses its homogeneity, which is detrimental to the focusing of the particle beam. This is a particularly sensitive issue because, on the one hand, the particle beam has its highest energy at the point of extraction and, on the other hand, it is more difficult to control the magnetic field at the peripheral edges of the magnet poles where the magnetic field drops rapidly. To enhance the focusing of an extracted particle beam, it has been proposed in the art to modify the geometry of the peripheral edges of hill sectors by forming protrusions to said peripheral edges by addition of gradient correctors. Gradient correctors are relatively small blocks of steel with respect to the size of a hill sector, which are coupled to the peripheral surfaces of the hill sectors. Such gradient correctors allow the modification of the magnetic field near the peripheral edges and thus locally modify the magnetic field near the peripheral edge of a hill sector to improve the focusing of the outgoing particle beam. The use of protruding gradient correctors has, however, several drawbacks. First, the volume of the vacuum chamber hosting the magnet poles must be increased accordingly, thus requiring more

energy and time to pump the gases from the vacuum chamber. Second, the overall weight of the cyclotron is increased because of, on the one hand, the weight of the gradient correctors themselves and, on the other hand, the increased overall size of the outer walls of the vacuum chamber and, consequently, the size of the flux return yoke; both contributing to a substantial increase of the cyclotron weight. Third, the position of the protruding gradient correctors is essential; small deviations of position may yield large variations of the magnetic field. Gradient correctors must be fixed manually by a skilled artisan at precisely the same position of the peripheral surface of all the hill sectors. This is of course, a critical and expensive operation. Fourth, these protruding gradient correctors have the effect of deviating the magnetic field outwards, which pulls outwards the path of the particle beam towards the peripheral edge of a hill gap portion between a pair of opposed hill sectors where the magnetic field loses its homogeneity. This shift also leads to a loss of useful magnetic field and thus requires an increase of the coil current in order to compensate this loss. It is therefore more difficult and expensive to control the properties of the extracted particle beam.

[0007] US3398308 describes a device for improving the symmetry of the magnetic field to which particles are subjected during acceleration in a cyclotron including a particle extraction system having magnetic components disposed in a peripheral portion of the cyclotron magnetic field region. The device includes several sets of dummy components equal in number to one less than the total number of cyclic variations of the composite magnetic field in the cyclotron. In order to lower the magnitude of the magnetic field adjacent the particle extraction system, the geometry of the edge of the magnet pole can be modified by radially displacing inwardly a portion of the edge so as to be parallel to the path of the beam exiting the cyclotron.

[0008] There therefore remains a need in the art to provide an isochronous sector-focused cyclotron allowing the extraction of a more focused and more predictable particle beam in an efficient and cost effective manner.

Summary of the invention

[0009] The present invention is defined in the appended independent claims. Preferred embodiments are defined in the dependent claims.

[0010] The present invention concerns a magnet pole for a cyclotron comprising at least 3 hill sectors and a same number of valley sectors comprising a bottom surface, said hill sectors and valley sectors being alternatively distributed around a central axis, Z, each hill sector comprising:

(a) an upper surface defined by:

- an upper peripheral edge, said upper peripheral edge being bounded by a first and a second upper distal ends, and being defined as the edge of the upper surface located furthest from the central axis;
- an upper central edge, said upper central edge being bounded by a first and a second upper proximal ends and being defined as the edge of the upper surface located closest from the central axis;
- a first upper lateral edge connecting the first upper distal end and first upper proximal end;
- a second upper lateral edge connecting the second upper distal end and second upper proximal end;

(b) a first and second lateral surfaces each extending transversally from the first and second upper lateral edges, to the bottom surfaces of the corresponding valley sectors located on either sides of a hill sector, thus defining a first and second lower lateral edges as the edges intersecting a lateral surface with an adjacent bottom surface, said first and second lower lateral edges each having a lower distal end located furthest from the central axis;

(c) a peripheral surface extending from the upper peripheral edge to a lower peripheral line defined as the segment bounded by the lower distal ends of the first and second lower lateral edges;

wherein the upper peripheral edge of at least one hill sector comprises a concave portion with respect to the central axis defining a recess extending at least partially over a portion of the peripheral surface of the corresponding hill sector.

[0011] The recess is generally wedge shaped with a first and second converging lines (preferably straight lines) extending away from the upper peripheral edge, with a converging angle, θ , comprised between 70° and 130° , preferably between 80° and 110° , most preferably $90^\circ \pm 5^\circ$.

[0012] The recess can have a converging portion, away from the upper peripheral edge, said converging portion having one of the following geometry:

- a sharp corner forming a triangular recess;
- a straight edge forming a trapezoidal recess; or
- a rounded edge forming an arched recess.

[0013] Preferably, the upper peripheral edge has an azimuthal length, A_h , and wherein the concave portion extends

between 3% and 30% of the azimuthal length of the upper peripheral edge, preferably, between 5% and 20%, more preferably, between 8% and 15%.

[0014] Preferably, the recess is separated from the first and second upper lateral edges. Alternatively, the recess is adjacent to the first upper lateral edge.

[0015] The recess can extend over a portion of the peripheral surface.

[0016] Preferably, the portion of the peripheral surface correspond to a fraction, ζ , of the height of the peripheral surface measured parallel to the central axis between the upper peripheral edge and the lower peripheral line, wherein the fraction, ζ , is comprised between 25% and 75%, preferably between 40% and 60%, most preferably between 45% and 55%.

[0017] In order to have smooth variations of the magnetic field, the peripheral surface forms a chamfer adjacent to the upper peripheral edge.

[0018] Preferably, the upper peripheral edge is an arc of circle which centre is offset with respect to the central axis, and which radius is not more than 85% of a distance from the central axis to a midpoint of the upper peripheral edge, which is equidistant to the first and second upper distal ends.

[0019] The number, N, of hill sectors is preferably 3, 4, 5, 6, 7, or 8, more preferably N = 4.

[0020] The invention also relates to a cyclotron for accelerating a particle beam over a given path comprised within a gap, said cyclotron comprising first and second magnet poles such as described above, wherein the first and second magnet poles are positioned symmetrically with respect to a median plane normal to the central axes of first and second magnet pole forming said gap in between, with hill gap portion being formed between two opposite hill sectors and valley gap portions being formed between two opposite valley sectors.

[0021] Preferably, the recess of a cyclotron has a first and a second recess distal points, said first and second recess distal points being separated from one another by a distance L10, and wherein the hill gap portion between a pair of hill sectors of the first and second magnet poles has an average height, Gh, and wherein the ratio Gh / L10 is comprised between 5 and 100 %, preferably between 10 and 50 %, more preferably, 20 and 33 %.

[0022] The cyclotron can also comprise a point of extraction, located in a hill gap portion between two opposite upper surfaces of hill sectors of the first and second magnet poles, wherein the given path of the particle beam is an outward spiral path cycling about the central axis until said first point of extraction whence the particle beam can be driven out of the cyclotron with a given energy along an extraction path, and wherein the recess is located downstream from said point of extraction wherein downstream is defined with respect to the direction of the particle beam, such that the extraction path crosses on line of the recess with an angle comprised between 80 and 100°, preferably between, 85 and 95°.

[0023] Preferably, the cyclotron further comprises a second point of extraction in a hill sector defining a second extraction path, and comprising a second recess located downstream from the second point of extraction, such that the second extraction path crosses one line of the second recess with an angle comprised between 80 and 100°, preferably between, 85 and 95°.

Short description of the drawings

[0024] These and further aspects of the invention will be explained in greater detail by way of example and with reference to the accompanying drawings in which:

Fig. 1 schematically shows (a) a side cut view and (b) a top view of a cyclotron according to the invention;

Fig. 2 shows an example of hill and valley sectors of a cyclotron according to the invention;

Fig. 3 shows a partial perspective view of a half cyclotron and the path of accelerates charged particles (the outlets for the extracted particles in the flux return yokes are not shown for enhancing visibility);

Fig. 4 shows an example of a hill sector according to the present invention comprising a gradient corrector;

Fig. 5 shows an example of lines of a magnetic field with and without gradient corrector;

Fig. 6 shows examples of geometries of the concave portion of the upper peripheral line of a hill sector according to the present invention;

Fig. 7 shows examples of geometries of the recess according to the present invention;

Fig. 8 shows an example of a magnet pole according to the present invention having two recesses and two points of extraction

Fig. 9 shows another example of a hill sector according to the present invention comprising an improved upper peripheral edge design of a hill sector;

Fig. 10 shows a third example of a hill sector according to the present invention and having a recess (a) and a pole insert (b).

Detailed description

Geometry of a cyclotron according to the present invention

[0025] The present invention concerns isochronous sector-focused cyclotrons, hereafter referred to as cyclotron of the type discussed in the technical background section supra. As illustrated in Fig. 3, a cyclotron according to the present invention accelerates charged particles outwards from a central area of the cyclotron along a spiral path 12 until they are extracted at energies of several MeV. For example, the charged particles thus extracted can be protons, H^+ , or deuteron, D^+ . Preferably, the energy reached by the extracted particles is comprised between 5 and 30 MeV, more preferably between 15 and 21 MeV, most preferably 18 MeV. Cyclotrons of such energies are used, for example, for producing short-lived positron-emitting isotopes suitable for use in PET imaging (positron emitting tomography) or for producing gamma-emitting isotopes, for example, Tc99m, for SPECT imaging (single photon emission computed tomography).

[0026] As illustrated in Fig. 1 a cyclotron 1 according to the present invention comprises two base plates 5 and flux return yokes 6 which, together, form a yoke. The flux return yokes form the outer walls of the cyclotron and control the magnetic field outside of the coils 14 by containing it within the cyclotron. It further comprises first and second magnet poles 2 located in a vacuum chamber, facing each other symmetrically with respect to a median plane MP normal to a central axis, Z, and separated from one another by a gap 7. The yoke and the magnet poles are all made of a magnetic material, preferably a low carbon steel and form a part of the magnetic system. The magnetic system is completed by a first and second coils 14 made of electrically conductive wires wound around the first and second magnet poles and fitting within an annular space defined between the magnet poles and the flux return yokes.

[0027] As illustrated in Fig. 1(b) and Fig. 2, each of the first and second magnet poles 2 comprises at least $N = 3$ hill sectors 3 distributed radially around the central axis, Z (Fig. 1(b) illustrates a preferred embodiment with $N = 4$). Each hill sector 3, represented in Fig. 1(b) as light shaded areas, has an upper surface 3U extending over a hill azimuthal angle, α_h . Each of the first and second magnet poles 2 further comprises the same number, N, of valley sectors 4, represented in Fig. 1(b) as dark shaded areas, distributed radially around the central axis Z. Each valley sector 4 is flanked by two hill sectors 3 and has a bottom surface 4B extending over a valley azimuthal angle, α_v , such that $\alpha_h + \alpha_v = 360^\circ/N$.

[0028] The hill sectors 3 and valley sectors 4 of the first magnet pole 2 face the opposite hill sectors 3 and valley sectors 4, respectively, of the second magnet pole 2. The path 12 followed by the particle beam illustrated in Fig. 3 is comprised within the gap 7 separating the first and second magnet poles. The gap 7 between the first and second magnet poles thus comprises hill gap portions 7h defined between the upper surfaces 3U of two opposite hill sectors 3 and valley gap portions 7v defined between the bottom surfaces 4B of two opposite valley sectors 4. The hill gap portions 7h have an average gap height, Gh, defined as the average height of the hill gap portions over the areas of two opposite upper surfaces 3U.

[0029] Average hill and valley gap heights are measured as the average of the gap heights over the whole upper surface and lower surface of a hill sector and a valley sector, respectively. The average of the valley gap height ignores any opening on the bottom surfaces.

[0030] The upper surface 3U is defined by (see Fig. 2):

- an upper peripheral edge 3up, said upper peripheral edge being bounded by a first and a second upper distal ends 3ude, and being defined as the edge of the upper surface located furthest from the central axis Z;
- an upper central edge 3uc, said upper central edge being bounded by a first and a second upper proximal ends 3upe and being defined as the edge of the upper surface located closest from the central axis;
- a second upper lateral edge 3ul connecting the second upper distal end and second upper proximal end.

[0031] A hill sector 3 further comprises (see Fig. 2):

- a first and second lateral surfaces 3L each extending transversally from the first and second upper lateral edges, to the bottom surfaces of the corresponding valley sectors located on either sides of a hill sector, thus defining a first and second lower lateral edges 3ll as the edges intersecting a lateral surface with an adjacent bottom surface, said first and second lower lateral edges each having a lower distal end 3lde located furthest from the central axis;
- a peripheral surface 3P extending from the upper peripheral edge to a lower peripheral line 3lp defined as the segment bounded by the lower distal ends 3lde of the first and second lower lateral edges.

[0032] The average height of a hill, Hh, sector is the average distance measured parallel to the central axis between lower and upper lateral edges.

[0033] An end of an edge is defined as one of the two extremities bounding a segment defining the edge. A proximal end is the end of an edge located closest from the central axis, **Z**. A distal end is the end of an edge located furthest from the central axis, **Z**. An end can be a corner point which is defined as a point where two or more lines meet. A corner point can also be defined as a point where the tangent of a curve changes sign or presents a discontinuity.

[0034] An edge is a line segment where two surfaces meet. An edge is bounded by two ends, as defined supra, and defines one side of each of the two meeting surfaces. For reasons of machining tools limitations, as well as for reduction of stress concentrations, two surfaces often meet with a given radius of curvature, **R**, which makes it difficult to define precisely the geometrical position of the edge intersecting both surfaces. In this case, the edge is defined as the geometric line intersecting the two surfaces extrapolated so as to intersect each other with an infinite curvature ($1/R$). An upper edge is an edge intersecting the upper surface **3U** of a hill sector, and a lower edge is an edge intersecting the bottom surface **4B** of a valley sector.

[0035] A peripheral edge is defined as the edge of a surface comprising the point located the furthest from the central axis, **Z**. If the furthest point is a corner point shared by two edges, the peripheral edge is also the edge of a surface which average distance to the central axis, **Z**, is the largest. For example, the upper peripheral edge is the edge of the upper surface comprising the point located the furthest to the central axis. If a hill sector is compared to a slice of tart, the peripheral edge would be the peripheral crust of the tart.

[0036] In an analogous manner, a central edge is defined as the edge of a surface comprising the point located the closest to the central axis, **Z**. For example, the upper central edge is the edge of the upper surface comprising the point located the closest to the central axis, **Z**.

[0037] A lateral edge is defined as the edge joining a central edge at a proximal end to a peripheral edge at a distal end. The proximal end of a lateral edge is therefore the end of said lateral edge intersecting a central edge, and the distal end of said lateral edge is the end of said lateral edge intersecting a peripheral edge.

[0038] Depending on the design of the cyclotron, the upper / lower central edge may have different geometries. The most common geometry is a concave line (or concave curve), often circular, of finite length ($\neq 0$), with respect to the central axis, which is bounded by a first and second upper / lower proximal ends, separated from one another. This configuration is useful as it clears space for the introduction into the gap of the particle beam and other elements. In a first alternative configuration, the first and second proximal central ends are merged into a single proximal central point, forming a summit of the upper surface **3U**, which comprises three edges only, the central edge having a zero-length. If a hill sector is again compared to a slice of tart, the pointed tip of the slice would correspond to the central edge thus reduced to a single point. In a second alternative configuration, the transition from the first to the second lateral edges can be a curve convex with respect to the central axis, **Z**, leading to a smooth transition devoid of any corner point. In this configuration, the central edge is also reduced to a single point defined as the point wherein the tangent changes sign. Usually, even in the first and second alternative configurations, a hill sector does not extend all the way to the central axis, the central area directly surrounding the central axis is cleared to allow insertion of the particle beam or installation of other elements.

[0039] As shown in Fig. 2, the first and second lateral surfaces **3L** are preferably chamfered forming a chamfer **3ec** at the first and second upper lateral edges, respectively. A chamfer is defined as an intermediate surface between two surfaces obtained by cutting off the edge which would have been formed by the two surfaces absent a chamfer. A chamfer reduces the angle formed at an edge between two surfaces. Chamfers are often used in mechanics for reducing stress concentrations. In cyclotrons, however, a chamfered lateral surface at the level of the upper surface of a hill sector enhances the focusing of the particle beam as it reaches a hill gap portion **7h**. The peripheral surface **3P** of a hill sector can also form a chamfer at the upper peripheral edge, which improves the homogeneity of the magnetic field near the peripheral edge.

[0040] A cyclotron according to the present invention preferably comprises $N = 3$ to 8 hill sectors **3**. More preferably, as illustrated in the Figures, $N = 4$. For even values of N , the hill sectors **3** and valley sectors **4** must be distributed about the central axis with any symmetry of $2n$, with $n = 1$ to $N/2$. Preferably, $n = N/2$, such that all the N hill sectors are identical to one another, and all the N valley sectors are identical to one another. For odd values of N , the hill sectors **3** and valley sectors **4** must be distributed about the central axis with a symmetry of N . In a preferred embodiment, the N hill sectors **3** are uniformly distributed around the central axis for all $N = 3-8$ (i.e., with a symmetry of N). The first and second magnet poles **2** are positioned with their respective upper surfaces **3U** facing each other and symmetrically with respect to the median plane **MP** normal to the respective central axes **Z** of the first and second magnet poles **2**, which are coaxial.

[0041] The shape of the hill sectors is often wedge shaped like a slice of tart (often, as discussed supra, with a missing tip) with the first and second lateral surfaces **3L** converging from the peripheral surface towards the central axis **Z** (usually without reaching it). The hill azimuthal angle, α_h , corresponds to the converging angle, measured at the level of the intersection point of the (extrapolated) upper lateral edges of the lateral surfaces at, or adjacent to, the central axis **Z**. The hill azimuthal angle, α_h , is preferably comprised between $360^\circ / 2N \pm 10^\circ$, more preferably between $360^\circ / 2N \pm 5^\circ$, most preferably between $360^\circ / 2N \pm 2^\circ$.

[0042] The valley azimuthal angle α_v , measured at the level of the central axis **Z** is preferably comprised between

$360^\circ / 2N \pm 10^\circ$, more preferably between $360^\circ / 2N \pm 5^\circ$, most preferably between $360^\circ / 2N \pm 2^\circ$. The valley azimuthal angle α_v can be equal to the hill azimuthal angle, α_h . In case of a degree of symmetry of N , $\alpha_v = 360^\circ / N - \alpha_h$; for example, for $N = 4$, α_v is the complementary angle of α_h , with $\alpha_v = 90^\circ - \alpha_h$.

[0043] The largest distance, **Lh**, between the central axis and a peripheral edge is preferably comprised between 200 and 2000 mm, more preferably between 400 and 1000 mm, most preferably between 500 and 800 mm. For a 18 MeV proton cyclotron, the longest distance, **Lh**, is usually less than 750 mm, and can be of the order of 500 to 750 mm, typically 520 to 550 mm. The upper peripheral edge has an azimuthal length, **Ah**, measured between the first and second upper peripheral ends, and can be approximated to, $Ah = Lh \times \alpha_h$ [rad].

[0044] The two magnet poles **2** and solenoid coils **14** wound around each magnet pole, form an (electro-)magnet which generates a magnetic field in the gap **7** between the magnetic poles that guides and focuses the beam of charged particles (= particle beam) along a spiral path **12** illustrated in Fig. 3, starting from the central area (around the central axis, **Z**) of the cyclotron, until it reaches a target energy, for example of 18 MeV, whence it is extracted. As discussed supra, the magnet poles are divided into alternating hill sectors and valley sectors distributed around the central axis, **Z**. A strong magnetic field is thus created in the hill gap portions **7h** of average height **Gh** within the hill sectors and a weaker magnetic field is created in the valley gap portions **7v** of average height **Gv** > **Gh**, within the valley sectors thus creating vertical focusing of the particle beam.

[0045] When a particle beam is introduced into a cyclotron, it is accelerated by an electric field created between high voltage electrodes called dees (not shown), and ground voltage electrodes attached to the lateral edges of the poles, positioned in the valley sectors, where the magnetic field is weaker. Each time an accelerated particle penetrates into a hill gap portion **7h** it has a higher speed than it had in the preceding hill sector. The high magnetic field present in a hill sector deviates the trajectory of the accelerated particle to follow an essentially circular path of radius larger than it followed in the preceding hill sector. Once a particle beam has been accelerated to its target energy, it is extracted from the cyclotron at a point called point of extraction **PE**, as shown in Fig. 3. For example, energetic protons, H^+ , can be extracted by driving a beam of accelerated H^- ions through a stripper consisting of a thin foil sheet of graphite. A H^- ion passing through the stripper loses two electrons to become a positive, H^+ . By changing the sign of particle charge, the curvature of its path in the magnetic field changes sign, and the particle beam is thus led out of the cyclotron towards a target (not shown). Other extracting systems are known by the persons skilled in the art and the type and details of the extraction system used is not essential to the present invention. Usually, a point of extraction is located in a hill gap portion **7h**. A cyclotron can comprise several points of extraction in a same hill portion. Because of the symmetry requirements of a cyclotron, more than one hill sector comprises an extraction point. For degrees of symmetry of N , all N hill sectors comprise the same number of points of extraction. The points of extraction can be used individually (one only at a time) or simultaneously (several at a time).

Gradient corrector

[0046] Fig. 4(a) and Fig. 4(b) show an example of a preferred embodiment of a magnet pole for a cyclotron comprising $N = 4$ hill sectors and $N = 4$ valley sectors comprising a bottom surface, said hill sectors and valley sectors alternatively distributed around a central axis, **Z**, with a symmetry of $N = 4$. Such hill sector of cyclotron according to the present invention comprises a first and second lateral surfaces **3L**, a peripheral surface **3P** and an upper surface **3U** such as defined above. The upper peripheral edge **3up** of the upper surface of at least one hill sector comprises a convex portion adjacent to a concave portion with respect to the central axis defining a recess extending partially over a portion of the peripheral surface of the corresponding hill sector. Preferably, The upper peripheral edge **3up** of the upper surface of at least one hill sector comprises 2 convex portions separated by a concave portion.

[0047] Because of the symmetry requirements of $2n$ for even values of N and of N for odd values of N , discussed supra, the same symmetry must apply to the presence or not of a concave portion with respect to the central axis on the upper peripheral edges of the various hill sectors. Therefore, the upper peripheral edge of each hill sector, preferably, comprises a concave portion **3upc** with respect to the central axis defining a recess **10** extending partially over the peripheral surface of the corresponding hill sector between two convex portions.

[0048] The term "concave" means curving in or hollowed inward. The concave portion with respect to the central axis of an edge, is a portion of the edge curving towards the central axis. This term is opposed to the term "convex" that means curving out of or extending outward from the central axis.

[0049] The position of the recess can either be separated from the first and second lateral edges, or adjacent to the first or second lateral edge. Preferably, a hill sector comprises at least one recess separated from the lateral edges.

[0050] In prior art cyclotrons, protruding gradient correctors were used. Protruding gradient correctors have several drawbacks:

- increase of the volume of the vacuum chamber,
- increase of the volume of the yoke, and of the whole cyclotron,

- increase of the weight of the cyclotron,
- difficulty of precise positioning of the gradient correctors which must be done manually,
- outwards deviation of the magnetic field.

[0051] Using recessed gradient correctors instead of protruding gradient correctors has several advantages. First, it allows the reduction of the size of the vacuum chamber hosting the magnet poles leading to a decrease of energy required for evacuating the gases from the vacuum chamber and reducing the time of the gas evacuation. Second, the overall weight of the cyclotron is decreased because, on the one hand, the weight of the hill sectors is slightly reduced instead of being increased and, on the other hand, the overall diameter of the inner surface of flux return yoke is decreased. Third, the position of the recesses can be precisely manufactured and positioned by numerically controlled machining allowing the optimization of the angle at which the particle beam crosses the peripheral edge of the hill sector. Fourth, when protruding gradient correctors deviate the magnetic field outwards, the magnetic field is deviated inwards by recessed gradient correctors resulting in an inwards shift of the last cycles of the particles path, further away from the peripheral edge of the hill sector, where the magnetic field is more uniform than close to the peripheral edge. Fig. 4 shows an example of the lines of the magnetic field deviated by the recessing gradient corrector (Fig. 5(a)) and without any gradient corrector (Fig. 5(b)). It is therefore easier and more predictable to control the properties of the extracted particle beam, and particularly the focusing thereof. This deviation towards the acceleration area also allows the power fed to the coils to be decreased.

[0052] Preferably, the upper peripheral edge **3up** comprises a first and a second recess distal points **10rdp**, defining the boundaries of a recess, and which are defined as the points where the tangent of the upper peripheral edge changes sign or presents a discontinuity. The first and second recess distal points are separated from one another by a distance **L10**. The recess also comprises a recess proximal point **10rpp** defined as the point of the recess located closest to the central axis, **Z**. The first and second recess distal points **10rdp** join the recess proximal point **10rpp** by a first and second recess converging edges **10rc**.

[0053] The recess depth, **H10**, is defined as the height of the triangle formed by the first and second recess distal points **10rdp** and the recess proximal point **10rpp**, and passing by the recess proximal point **10rpp**. The depth of the recess, **H10** is comprised between 3% and 30%, preferably, between 5% and 20%, more preferably, between 8% and 15% of the azimuthal length, **Ah**, of the upper peripheral edge. Preferably, the ratio of the recess depth, **H10**, to the largest distance, **Lh**, between the central axis and a peripheral edge of a hill sector, $H10 / Lh$, is comprised between 2% and 20%, preferably, between 4% and 15%, more preferably, between 6% and 10%.

[0054] The upper peripheral edge **3up** has an azimuthal length, **Ah**, measured between the first and second upper distal ends **3ude**. The first recess converging edge **10r1** joining the first recess distal point to the recess proximal point has a length **L101** and the second recess converging edge **10r2** joining the second recess distal point to the recess proximal point has a length **L102**. The lengths **L101** and **L102** of the first and second recess converging edges are comprised between 5 and 30% of the azimuthal length, **Ah**, of the upper peripheral edge. Preferably, the length **L101** is equal $\pm 40\%$ to the length **L102** ($L101 = L102 \pm 40\%$).

[0055] Preferably, the distance **L10** between first and second recess distal points ranges between 5% and 50%, more preferably, between 10% and 30%, most preferably, between 15% and 20% of the azimuthal length, **Ah**, of the upper peripheral edge.

[0056] Preferably, the recess also extends over a portion of the peripheral surface **3P** from the upper peripheral edge **3up** towards the lower peripheral line **3lp**. The recess thus extends over the peripheral surface over a fraction, ζ , of a height of the peripheral surface measured parallel to the central axis between the upper peripheral edge and lower peripheral line. The fraction, ζ , is preferably, comprised between 25% and 100%, preferably between 40% and 75%, most preferably between 45% and 55%.

[0057] As illustrated in Fig. 6, the concave portion of the upper peripheral edge can have any of the following geometries open between the first and second recess distal points: (a) a rectangle, (b) a trapeze, (c) a triangle having straight edges or curved (inwards or outwards) edges, (d) an arc of circle, (e) two arcs of circle, (f) a parabola, (g) a square, (h) a parallelogram, (i) a polygon, (j) a smooth curve. Basically, any geometry determined by numerical analysis can be implemented. For example, in the case of a trapeze, the small base can comprise the recess proximal point **10rpp**, and the large base can be defined by the first and second recess distal points **10rdp**. Alternatively, the small base can be defined by the first and second recess distal points **10rdp**, and the large base can comprise the recess proximal point **10rpp**. A triangle can be scalene, isosceles or equilateral. It can also be right, with the right angle formed at the recess proximal point **10rpp**. In the case of two (or more) arc of circle, they can be curved inwards ((e) right) or outwards ((e) left). The concave portion is preferably designed such that one edge thereof intersects the extraction path of a particle beam with an angle of 80-100°, preferably 85-95°, substantially 90°.

[0058] Preferably, a recess **10** extends over a portion of the peripheral surface parallel to the central axis. Alternatively, it can extend downwards from the upper surface with an angle with the central axis, **Z**. The distance **L10** and/or the height **H10** can increase or decrease independently of one another or simultaneously along the height of the peripheral

surface. The area of the cross-section of the recess normal to the central axis, **Z**, can thus decrease or increase with the distance from the upper surface. In a more complex embodiment, the geometry and the area of the cross-section of the recess can change over the peripheral surface. The height of the recess can also vary over the peripheral surface. Fig. 7 illustrates some examples of geometries of recesses. For example, the recess can have a shape of: (a) a prism extending from the upper surface parallel to the central axis, (b) a prism extending from the peripheral surface normal to the central axis, (c) a (portion of) pyramid, or more complex volumes extending over the peripheral surface.

[0059] Preferably, the recess is generally wedge shaped with the first and second recess converging edges being straight (or slightly curved inwards or outwards) lines. The tip of the wedge corresponds to the recess proximal point and points at the general direction of the central axis. The converging angle, θ , at the tip of the wedge is preferably comprised between 70° and 130° , more preferably between 80° and 110° , most preferably $90^\circ \pm 5^\circ$. The expressions "inwards" and "outwards" used herein are to be understood as "towards" or "away from" the central axis, respectively.

[0060] More generally, the converging portion of the wedge-shaped recess can have one of the following geometries:

- a sharp corner forming a triangular recess, corresponding to the wedge shaped recess discussed supra;
- a straight edge forming a trapezoidal recessed wedge; or
- a rounded edge wedge forming an arched recess.

[0061] The present invention also concerns a cyclotron comprising magnet poles as defined supra. As described supra, a cyclotron accelerates a particle beam over a given path until a first point of extraction whence the particle beam is driven out of the cyclotron with a given energy. The hill gap portion between a pair of hill of the first and second magnet poles of a cyclotron has an average height, **Gh**. Preferably, the ratio of the distance **L10** between first and second recess distal points **10rdp** to the height of hill gap portion **Gh**, is comprised between 1 and 20, preferably between 2 and 10, more preferably, 3 and 5. For example, for a hill gap of height **Gh** = 20-40 mm, the distance **L10**, can be of the order of 10-100 mm, yielding a ratio **L10/Gh** which can be comprised between 1-5, preferably between 3 and 3.5, i.e. $Gh / L10 \leq 1$.

[0062] Preferably, a point of extraction is located within a hill gap portion adjacent to the peripheral edges of a pair of opposed hill sectors. A recess is located downstream from said first point of extraction wherein downstream is defined with respect to the direction of the particle beam. The recess **10** is precisely machined with respect to the point of extraction and to the extraction path such that the particle beam intersects the first converging recess edge **10r1** with an angle of $90^\circ \pm 15^\circ$. The particle beam thus leaves the hill gap portion substantially normal to the magnetic field, which improves the focusing of the extracted particle beam. The position and the geometry of the recess are determined by numerical computation and/or testing.

[0063] As shown in Fig. 8, the cyclotron may further comprise a second point of extraction, **PE2**, located downstream from the first point of extraction, **PE1**, and within the same hill gap portion of the same pair of opposed hill sectors. The particle beam can be driven out of the cyclotron at said second point of extraction with the same energy as at said first point of extraction. In this case, the hill sector comprising the two extraction points, also comprises two recesses, each located downstream from a corresponding point of extraction.

[0064] Fig. 9 shows an example of a preferred embodiment of a magnet pole for a cyclotron according to the present invention. In this embodiment, the upper peripheral edge **3up** is bounded by a first and a second upper distal ends, and the upper peripheral edge of a hill sector comprises an arc of circle **3ac** which centre is offset with respect to the central axis, and which radius, **Rh**, is not more than 85 % of a distance, **Lh**, from the central axis to a midpoint of the upper peripheral edge, which is equidistant to the first and second upper distal ends ($Rh / Lh \leq 85\%$).

[0065] Preferably, the ratio Rh / Lh of the radius, **Rh**, to the distance **Lh**, is not more than 75% ($Rh / Lh < 75\%$), more preferably not more than 65% ($Rh / Lh < 65\%$).

[0066] The aim of having the upper peripheral edge comprising an arc of circle which centre is offset with respect to the central axis is to homothetically approximate at least a portion of the upper peripheral edge to the highest energy (= last) orbit of the spiral path **12** in a hill gap portion **7h** of the cyclotron. By "homothetically approximate the orbit" is meant that the arc of circle portion of the upper peripheral edge and the last orbit of particle adjacent to the point of extraction are both arcs of circle sharing the same centre with different radii. The arc of circle is thus approximately parallel to the portion of said last orbit directly adjacent to and upstream from the extraction point. The length of the path of the extracted orbit and the angle between the orbit and the upper peripheral edge becomes independent of the azimuthal position of the extracting system (for example a stripper). In consequence, the characteristics of the extracted beam are (nearly) independent of the position of the point of extraction.

[0067] Preferably, the arc of circle extends from the first upper distal end to the second upper distal end of the upper peripheral edge, thus defining the whole peripheral edge of a hill sector and the centre of the arc of circle lies on the bisector of the upper surface, said bisector being defined as the straight line, joining the central axis to the midpoint of the upper peripheral edge.

[0068] Preferably, the peripheral surface forms a chamfer adjacent to the upper peripheral edge.

[0069] As described supra, a cyclotron accelerates the particle beam over a given path until a first point of extraction

whence the particle beam can be driven out of the cyclotron with a given energy. Advantageously, a hill sector may comprise more than one point of extraction, for example, two. The arc of circle portion of the upper peripheral edges of two opposite hill sectors with respect to the median plan **MP**, of two magnet poles are parallel to and reproduce homothetically a portion of the given path directly upstream of the first point of extraction. The arc of circle shares the same centre as, and is parallel to a portion of the given path over the whole peripheral edge. The terms "upstream" and "downstream" are defined with respect to the direction of the particle beam.

[0070] When the particle beam has reached its target energy, it is extracted at a point of extraction and, it then follows an extraction path downstream of the point of extraction. A part of this extraction path lies between the first and second magnet poles and is thus still comprised within the hill gap portion and subjected to the magnetic field. If the pair of opposite hill sectors comprises a first and a second points of extraction, the particle beam can be extracted either at the first or at the second point of extraction or at both. The particle beam then follows either a first or a second extraction path downstream of the first or second point of extraction. With the circular geometry of at least a portion of the upper peripheral edge according to the present embodiment, the length of the extraction path comprised within the gap downstream of the first point of extraction, **L1**, and the length of the extraction path comprised within the gap downstream of the second point of extraction, **L2**, are substantially equal.

[0071] The main advantage of having the same length of extraction paths downstream of the first and second points of extraction is to ensure that the particle beam extracted from one point of extraction has similar optical properties as the one extracted from the second point of extraction.

[0072] Fig. 10 shows an example of a preferred embodiment of a magnet pole for a cyclotron wherein the upper surface of at least one hill sector further comprises:

- a recess **8** extending over a length **L8** between a recess proximal end **8rpe** and a recess distal end **8rde** along a longitudinal axis **8rl** intersecting the upper peripheral edge and the upper central edge; said recess is separate from the first and second upper lateral edges over at least 80% of its length, **L8**, and
- a pole insert **9** having a geometry fitting said recess and being positioned in, and reversibly coupled to said recess.

[0073] The term "fitting" means that the pole insert has a general shape able to be precisely inserted into and nested in the recess.

[0074] In prior art cyclotrons comprising pole inserts, the pole inserts were positioned in a recess machined off a lateral edge of the upper surface of the hill sectors. Access to such pole inserts is, however, rendered difficult by part of the RF accelerating system overlapping the upper lateral edge area. Access to such pole inserts requires removing the overlapping part of the RF system first. By positioning a pole insert on the upper surface, it can be accessed easily and directly for removal, machining and reinsertion into the recess. With the present embodiment, it is thus much easier and efficient to reach the optimal insert topography yielding the predicted magnetic field and particle path.

[0075] Preferably, all pole inserts have the same shape and are made of the same material. Preferably, the pole insert is made of the same material as the corresponding hill sector.

[0076] Preferably, the recess extends along a longitudinal axis intersecting the central axis, and it is open ended at both ends and extends from the upper central edge all the way to the upper peripheral edge. In yet a preferred embodiment, the longitudinal axis intersects the upper peripheral edge at a point located at equal distance from the first and second upper distal ends, and wherein the first and second upper distal ends are preferably symmetrical with respect to the longitudinal axis. For example, except for the proximal portion **9p** adjacent to the central edge, the pole insert has a general parallelepiped shape, as illustrated in Fig. 6(b).

[0077] In the embodiment of Fig. 6(a), the recess extends to and is open ended at the upper peripheral edge, the distal end of the pole insert **9dc** forms a portion of the upper peripheral edge. The portion of the upper peripheral edge formed by the pole insert is preferably not more than 10%, more preferably not more than 5% of the length, **Ah**, of the upper peripheral edge. Preferably this distal end forms a chamfer at the peripheral surface.

[0078] The pole insert is nested in the recess and is reversibly fastened to the corresponding hill sector. For example, it can be coupled to the hill sector with screws.

[0079] As discussed supra, the pole insert preferably has a prismatic geometry along the longitudinal axis over at least 80% of its length, **L9**, excluding the converging proximal portion **9p**, of length **L9p**. The ridges between the hill upper surface **3U** and the hill lateral surfaces are chamfered, then the corresponding ridges of the proximal portion of the recess can be chamfered too.

[0080] The topography, illustrated in Fig. 6, of the pole insert upper surface **9U** and/or first and second lateral surfaces **9L** can be machined to form grooves **9gu**, **9gl** either transverse, or parallel to the longitudinal axis, of the upper surface or of a lateral surface. The grooves may extend along a straight, curved or broken line. Alternatively, holes **9hu**, **9hl** can be drilled through the surfaces. The holes can be blind holes (i.e., of finite depth) or can be through holes. As explained supra, each hill sector comprises a pole insert for symmetry reasons, the pole inserts are thus machined individually or aligned side by side and all machined together. The resulting aspect of the machined pole insert may differ considerably

from its aspect before machining.

[0081] In conclusion, the present invention offers the advantages that it allows the reduction of the size of the vacuum chamber and a decrease of the overall weight of the cyclotron. Third, the position of the recesses can be precisely manufactured and positioned. Fourth, the magnetic field is deviated inwards by recessed gradient correctors resulting in an inwards shift of the last cycles of the particles path where the magnetic field is more uniform than close to the peripheral edge. It is therefore easier and more predictable to control the properties of the extracted particle beam, and particularly the focusing thereof.

Ref #	Feature
1	Cyclotron
2	Magnet pole
3	Hill sector
4	Valley sector
5	Yokes
6	Flux return yoke
7	Gap
8	Recess
9	Pole insert
10	Recess
12	Spiral path
14	Coils
3ac	Arc of circle
3ec	Chamfered edge
3L	Lateral surface
3lde	Lower distal end of lower lateral edge
3ll	Lower lateral edge
3lp	Lower peripheral line
3P	Peripheral surface
3U	Upper surface
3uc	Upper central edge
3ude	Upper distal end of upper lateral edge
3ul	Upper lateral edge
3up	Upper peripheral edge
3upc	Upper peripheral edge concave portion
3upe	Upper proximal end of upper lateral edge
4B	Bottom surface
7h	Hill gap portion
7v	Valley gap portion
8lr	Recess longitudinal axis
8rde	Recess distal end
8rpe	Recess proximal end

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(continued)

	Ref #	Feature
5	9dc	Pole insert distal end chanfered
	9gl	Pole insert groove lateral
	9gu	Pole insert groove upper
	9hl	Pole insert hole lateral
10	9hu	Pole insert hole upper
	9L	Pole insert lateral surface
	9lp	Pole insert proximal portion length
15	9p	Pole insert proximal portion
	9pe	Pole insert proximal edge
	9U	Pole insert upper surface
	9pe	Pole insert proximal edge
20	9s	Screw
	9U	Pole insert upper surface
	10r1	Recess converging edge (1st)
25	10r2	Recess converging edge (2d)
	10rdp	Recess distal point
	10rpp	Recess proximal point
	Ah	Azimuthal length of the upper peripheral edge
30	dh	Distance upper peripheral edge - highest orbit
	Gh	Gap height at hill
	Gv	Gap height at valley
35	H10	Recess height
	Hh	Hill height
	L1, L2	Length of the extraction path comprised within the gap downstream of a point of extraction
	L10	Length between first and second recess distal points
40	L101, L102	Length of the recess converging edge
	L8	Recess length
	L9	Pole insert length
45	L9p	Pole insert length of proximal portion
	Lh	Distance between the central axis and a peripheral edge
	MP	Median plane
	PE	Point of extraction
50	Rh	Radius of radial pole contour
	Z	Central axis
	αh	Hill azimuthal angle
55	αv	Valley azimuthal angle

Claims

1. A magnet pole (2) for a cyclotron (1) comprising at least 3 hill sectors (3) and a same number of valley sectors (4) comprising a bottom surface (4B), said hill sectors and valley sectors being alternatively distributed around a central axis, Z, each hill sector comprising:

(a) an upper surface (3U) defined by:

- an upper peripheral edge (3up), said upper peripheral edge being bounded by a first and a second upper distal ends (3ude), and being defined as the edge of the upper surface located furthest from the central axis;
- an upper central edge (3uc), said upper central edge being bounded by a first and a second upper proximal ends (3upe) and being defined as the edge of the upper surface located closest from the central axis;
- a first upper lateral edge (3ul) connecting the first upper distal end and first upper proximal end;
- a second upper lateral edge (3ul) connecting the second upper distal end and second upper proximal end;

(b) a first and second lateral surfaces (3L) each extending transversally from the first and second upper lateral edges, to the bottom surfaces of the corresponding valley sectors located on either sides of a hill sector, thus defining a first and second lower lateral edges (3ll) as the edges intersecting a lateral surface with an adjacent bottom surface, said first and second lower lateral edges each having a lower distal end located furthest from the central axis;

(c) a peripheral surface (3P) extending from the upper peripheral edge to a lower peripheral line (3lp) defined as the segment bounded by the lower distal ends (3lde) of the first and second lower lateral edges;

wherein the upper peripheral edge of at least one hill sector comprises a concave portion with respect to the central axis defining a recess extending at least partially over a portion of the peripheral surface of the corresponding hill sector,

characterised in that, the recess is generally wedge shaped with a first and second converging lines extending away from the upper peripheral edge, with a converging angle, θ , comprised between 70° and 130° .

2. The magnet pole according to claim 1, wherein the converging angle, θ , is comprised between 80° and 110° , preferably $90^\circ \pm 5^\circ$.

3. The magnet pole according to claim 2, wherein the recess has a converging portion, away from the upper peripheral edge, said converging portion having one of the following geometry:

- a sharp corner forming a triangular recess;
- a straight edge forming a trapezoidal recess; or
- a rounded edge forming an arched recess.

4. The magnet pole according to any one of the previous claims, wherein the upper peripheral edge has an azimuthal length, A_h , and wherein the concave portion extends between 3% and 30% of the azimuthal length of the upper peripheral edge, preferably, between 5% and 20%, more preferably, between 8% and 15%.

5. The magnet pole according to any one of the previous claims, comprising a recess as defined in claim 1 which is separated from the first and second upper lateral edges.

6. The magnet pole according to any one of the previous claims, comprising a recess as defined in claim 1 which is adjacent to the first upper lateral edge.

7. The magnet pole according to any one of the previous claims, wherein the recess extends over a portion of the peripheral surface corresponding to a fraction, ζ , of a height of the peripheral surface measured parallel to the central axis between the upper peripheral edge and the lower peripheral line, wherein the fraction, ζ , is comprised between 25% and 75%, preferably between 40% and 60%, most preferably between 45% and 55%.

8. The magnet pole according to any one of the previous claims, wherein the peripheral surface forms a chamfer adjacent to the upper peripheral edge.

9. The magnet pole according to any one of the previous claims, wherein the upper peripheral edge is an arc of circle

which centre is offset with respect to the central axis, and which radius is not more than 85% of a distance from the central axis to a midpoint of the upper peripheral edge, which is equidistant to the first and second upper distal ends.

10. The magnet pole according to any one of the previous claims, wherein the number, N, of hill sectors is 3, 4, 5, 6, 7, or 8, preferably N = 4.

11. Cyclotron for accelerating a particle beam over a given path comprised within a gap, said cyclotron comprising first and second magnet poles according to any one of the previous claims, wherein the first and second magnet poles are positioned symmetrically with respect to a median plane normal to the central axes of the first and second magnet poles forming said gap in between, with hill gap portion being formed between two opposite hill sectors and valley gap portions being formed between two opposite valley sectors.

12. Cyclotron according to the previous claim, wherein the recess has a first and a second recess distal points, said first and second recess distal points being separated from one another by a distance L10, and wherein the hill gap portion between a pair of hill sectors of the first and second magnet poles has an average height, Gh, and wherein the ratio Gh / L10 is comprised between 5 and 100 %, preferably between 10 and 50 %, more preferably, 20 and 33 %.

13. Cyclotron according to any one of the claims 11 to 12, comprising a point of extraction, located in a hill gap portion between two opposite upper surfaces of hill sectors of the first and second magnet poles, wherein:

- the given path of the particle beam is an outward spiral path cycling about the central axis until said first point of extraction whence the particle beam can be driven out of the cyclotron with a given energy along an extraction path,
- the recess is located downstream from said point of extraction wherein downstream is defined with respect to the direction of the particle beam, such that
- the extraction path exits the corresponding hill gap portion by intersecting the recess with an angle comprised between 80 and 100°, preferably between, 85 and 95°.

14. Cyclotron according to claim 13, comprising a second point of extraction in a hill sector defining a second extraction path, and comprising a second recess located downstream from the second point of extraction, such that the second extraction path exits the corresponding hill gap portion by intersecting the second recess with an angle comprised between 80 and 100°, preferably between, 85 and 95°.

15. Cyclotron according to claim 14, wherein the first and second points of extraction are located on a same hill gap portion.

Patentansprüche

1. Magnetpol (2) für ein Zyklotron (1), umfassend mindestens 3 Hügelsektoren ("Hill"-Sektoren) (3) und dieselbe Anzahl an Talsektoren ("Valley"-Sektoren) (4), die eine Bodenfläche (4B) umfassen, wobei die Hill- und Valley-Sektoren alternierend um eine Zentralachse, Z, verteilt sind, wobei jeder Hill-Sektor umfasst:

(a)eine Oberseite (3U), die definiert ist durch:

- eine obere Umfangskante (3up), wobei die obere Umfangskante durch ein erstes und ein zweites oberes distales Ende (3ude) begrenzt ist und als die Kante der Oberseite definiert ist, die sich am weitesten von der Zentralachse entfernt befindet;
- eine obere Zentralkante (3uc), wobei die obere Zentralkante durch ein erstes und ein zweites oberes proximales Ende (3upe) begrenzt ist und als die Kante der Oberseite definiert ist, die sich am nächsten an der Zentralachse befindet;
- eine erste obere laterale Kante (3ul), die das erste obere distale Ende und das erste obere proximale Ende verbindet;
- eine zweite obere laterale Kante (3ul), die das zweite obere distale Ende und das zweite obere proximale Ende verbindet;

(b)eine erste und eine zweite laterale Fläche (3L), die sich jeweils quer von der ersten und zweiten oberen lateralen Kante zu den Bodenflächen der entsprechenden Valley-Sektoren erstrecken, die sich auf beiden Seiten eines Hill-Sektors befinden, wodurch eine erste und eine zweite untere laterale Kante (3ll) als die Kanten

definiert werden, an denen sich eine laterale Fläche und eine angrenzende Bodenfläche kreuzen, wobei die erste und die zweite untere laterale Kante jeweils ein unteres distales Ende aufweisen, das sich am weitesten von der Zentralachse entfernt befindet;

(c) eine Umfangsfläche (3P), die sich von der oberen Umfangskante zu einer unteren Umfangsfläche (3IP) erstreckt, die als das Segment definiert ist, welches durch die unteren distalen Enden (3Ide) der ersten und der zweiten unteren lateralen Kante begrenzt wird;

wobei die obere Umfangskante von mindestens einem Hill-Sektor einen konkaven Abschnitt in Bezug auf die Zentralachse umfasst, der eine Aussparung definiert, die sich mindestens teilweise über einen Abschnitt der Umfangsfläche des entsprechenden Hill-Sektors erstreckt,

dadurch gekennzeichnet, dass die Aussparung allgemein keilförmig ist, wobei erste und zweite konvergierende Linien sich mit einem Konvergierwinkel, θ , der zwischen 70° und 130° liegt, von der oberen Umfangskante weg erstrecken.

2. Magnetpol nach Anspruch 1, wobei der Konvergierwinkel, θ , zwischen 80° und 110° , vorzugsweise $90^\circ \pm 5^\circ$ liegt.

3. Magnetpol nach Anspruch 2, wobei die Aussparung einen konvergierenden Abschnitt weg von der oberen Umfangskante aufweist, wobei der konvergierende Abschnitt eine der folgenden Geometrien aufweist:

- eine scharfe Ecke, die eine dreieckförmige Aussparung bildet;
- eine gerade Kante, die eine trapezförmige Aussparung bildet; oder
- eine gerundete Kante, die eine bogenförmige Aussparung bildet.

4. Magnetpol nach einem der vorhergehenden Ansprüche, wobei die obere Umfangskante eine Azimutlänge, A_h , aufweist, und wobei der konkave Abschnitt sich über zwischen 3 % und 30 % der Azimutlänge der oberen Umfangskante erstreckt, vorzugsweise zwischen 5 % und 20 %, bevorzugter zwischen 8 % und 15 %.

5. Magnetpol nach einem der vorhergehenden Ansprüche, umfassend eine Aussparung wie in Anspruch 1 definiert, die von der ersten und zweiten oberen lateralen Kante getrennt ist.

6. Magnetpol nach einem der vorhergehenden Ansprüche, umfassend eine Aussparung wie in Anspruch 1 definiert, die sich benachbart zu der ersten oberen lateralen Kante befindet.

7. Magnetpol nach einem der vorhergehenden Ansprüche, wobei sich die Aussparung über einen Abschnitt der Umfangsfläche erstreckt, der einer Fraktion, ζ , einer Höhe der Umfangsfläche entspricht, die parallel zu der Zentralachse zwischen der oberen Umfangskante und der unteren Umfangsfläche gemessen wird, wobei die Fraktion, ζ , zwischen 25 % und 75 %, vorzugsweise zwischen 40 % und 60 %, am meisten bevorzugt zwischen 45 % und 55 % beträgt.

8. Magnetpol nach einem der vorhergehenden Ansprüche, wobei die Umfangsfläche eine Abschrägung benachbart zu der oberen Umfangskante bildet.

9. Magnetpol nach einem der vorhergehenden Ansprüche, wobei die obere Umfangskante ein Kreisbogen ist, dessen Zentrum in Bezug zu der Zentralachse versetzt ist, und dessen Radius nicht mehr als 85 % eines Abstands von der Zentralachse zu einem Mittelpunkt der oberen Umfangskante beträgt, der äquidistant zu dem ersten und zweiten oberen distalen Ende ist.

10. Magnetpol nach einem der vorhergehenden Ansprüche, wobei die Anzahl, N , der Hill-Sektoren 3, 4, 5, 6, 7 oder 8 beträgt, wobei vorzugsweise $N = 4$.

11. Zyklotron zum Beschleunigen eines Teilchenstrahls über einen gegebenen Pfad, der sich in einem Spalt befindet, wobei der Zyklotron erste und zweite Magnetpole gemäß einem der vorhergehenden Ansprüche umfasst, wobei die ersten und zweiten Magnetpole symmetrisch in Bezug auf eine Medianebene positioniert ist, die senkrecht zu den Zentralachsen der ersten und zweiten Magnetpole ist, zwischen denen der Spalt gebildet ist, wobei zwischen zwei gegenüber liegenden Hill-Sektoren Hill-Spaltabschnitte gebildet sind und zwischen zwei gegenüber liegenden Valley-Sektoren Valley-Spaltabschnitte gebildet sind.

12. Zyklotron nach einem der vorhergehenden Ansprüche, wobei die Aussparung einen ersten und einen zweiten distalen Aussparungspunkt aufweist, wobei die ersten und zweiten distalen Aussparungspunkte um einen Abstand

L10 voneinander getrennt sind, und wobei der Hill-Spaltabschnitt zwischen einem Paar von Hill-Sektoren der ersten und zweiten Magnetpole eine durchschnittliche Höhe, Gh, aufweist, und wobei das Verhältnis Gh / L10 zwischen 5 und 100 %, vorzugsweise zwischen 10 und 50 %, bevorzugter 20 und 33 % liegt.

5 13. Zyklotron nach einem der Ansprüche 11 bis 12, umfassend einen Extraktionspunkt, der sich in einem Hill-Spaltabschnitt zwischen zwei gegenüber liegenden Oberseiten von Hill-Sektoren der ersten und zweiten Magnetpole befindet, wobei:

- 10 • der gegebene Pfad des Teilchenstrahls ein auswärts weisender Spiralfad ist, der bis zu dem ersten Extraktionspunkt um die Zentralachse kreist, woraus der Teilchenstrahl mit einer gegebenen Energie entlang eines Extraktionspfads aus dem Zyklotron heraus getrieben werden kann,
- wobei die Aussparung sich nachgeordnet zu dem Extraktionspunkt befindet, wobei nachgeordnet in Bezug zu der Richtung des Teilchenstrahls definiert ist, so dass
- 15 • der Extraktionspfad aus dem entsprechenden Hill-Spaltabschnitt austritt, indem die Aussparung mit einem Winkel gekreuzt wird, der zwischen 80 und 100°, vorzugsweise zwischen 85 und 95° liegt.

14. Zyklotron nach Anspruch 13, umfassend einen zweiten Extraktionspunkt in einem Hill-Sektor, der einen zweiten Extraktionspfad definiert, und umfassend eine zweite Aussparung, die sich nachgeordnet zu dem zweiten Extraktionspunkt befindet, so dass der zweite Extraktionspfad aus dem entsprechenden Hill-Spaltabschnitt austritt, indem die zweite Aussparung in einem Winkel gekreuzt wird, der zwischen 80 und 100°, vorzugsweise zwischen 85 und 95° liegt.

15. Zyklotron nach Anspruch 14, wobei der erste und der zweite Extraktionspunkt sich auf demselben Hill-Spaltabschnitt befinden.

Revendications

1. Pôle magnétique (2) pour cyclotron (1) comprenant au moins 3 secteurs de colline (3) et un même nombre de secteurs de vallée (4) comprenant une surface inférieure (4B), lesdits secteurs de colline et secteurs de vallée étant alternativement répartis autour d'un axe central, Z, chaque secteur de colline comprenant :

(a) une surface supérieure (3U) définie par :

- une arête périphérique supérieure (3up), ladite arête périphérique supérieure étant délimitée par une première et une seconde extrémité distale supérieure (3ude), et étant définie comme l'arête de la surface supérieure située la plus éloignée de l'axe central ;
- une arête centrale supérieure (3uc), ladite arête centrale supérieure étant délimitée par une première et une seconde extrémité proximale supérieure (3upe) et étant définie comme l'arête de la surface supérieure située la plus près de l'axe central ;
- une première arête latérale supérieure (3ul) reliant la première extrémité distale supérieure et la première extrémité proximale supérieure ;
- une seconde arête latérale supérieure (3ul) reliant la seconde extrémité distale supérieure et la seconde extrémité proximale supérieure ;

(b) une première et une seconde surface latérale (3L) s'étendant chacune transversalement à partir des première et seconde arêtes latérales supérieures jusqu'aux surfaces inférieures des secteurs de vallée correspondants situés de part et d'autre d'un secteur de colline, définissant ainsi une première et une seconde arêtes latérales inférieures (3Il) lorsque les arêtes coupent une surface latérale avec une surface inférieure adjacente, lesdites première et seconde arêtes latérales inférieures ayant chacune une extrémité distale inférieure située plus loin de l'axe central ;

(c) une surface périphérique (3P) s'étendant de l'arête périphérique supérieure à une ligne périphérique inférieure (3Ip) définie comme le segment délimité par les extrémités distales inférieures (3Ide) des première et seconde arêtes latérales inférieures ;

l'arête périphérique supérieure d'au moins un secteur de colline comprenant une partie concave par rapport à l'axe central définissant un évidement s'étendant au moins partiellement sur une partie de la surface périphérique du secteur de colline correspondant,

caractérisé en ce que l'évidement est généralement en forme de coin avec une première et une seconde ligne

convergente s'étendant à partir de l'arête périphérique supérieure, avec un angle de convergence, θ , compris entre 70° et 130°.

- 5 2. Pôle magnétique selon la revendication 1, l'angle de convergence θ étant compris entre 80° et 110°, de préférence 90° $\pm$ 5°.
3. Pôle magnétique selon la revendication 2, l'évidement ayant une partie convergente, éloignée de l'arête périphérique supérieure, ladite partie convergente ayant l'une des géométries suivantes :
10
 - un coin pointu formant un renforcement triangulaire ;
 - une arête droite formant un évidement trapézoïdal ; ou
 - une arête arrondie formant un évidement arqué.
- 15 4. Pôle magnétique selon l'une quelconque des revendications précédentes, l'arête périphérique supérieure ayant une longueur azimutale, Ah, et la partie concave s'étendant entre 3 % et 30 % de la longueur azimutale de l'arête périphérique supérieure, de préférence entre 5 % et 20 %, plus préférablement entre 8 % et 15 %.
5. Pôle magnétique selon l'une quelconque des revendications précédentes, comprenant un évidement selon la revendication 1, qui est séparé des première et seconde arêtes latérales supérieures.
20
6. Pôle magnétique selon l'une quelconque des revendications précédentes, comprenant un évidement selon la revendication 1, qui est adjacent à la première arête latérale supérieure.
- 25 7. Pôle magnétique selon l'une quelconque des revendications précédentes, l'évidement s'étendant sur une partie de la surface périphérique correspondant à une fraction, ξ , d'une hauteur de la surface périphérique mesurée parallèlement à l'axe central entre l'arête périphérique supérieure et la ligne périphérique inférieure, la fraction, ξ , étant comprise entre 25 % et 75 %, de préférence entre 40 % et 60 %, plus préférablement entre 45 % et 55 %.
- 30 8. Pôle magnétique selon l'une quelconque des revendications précédentes, la surface périphérique formant un chanfrein adjacent à l'arête périphérique supérieure.
9. Pôle magnétique selon l'une quelconque des revendications précédentes, l'arête périphérique supérieure étant un arc de cercle dont le centre est décalé par rapport à l'axe central et dont le rayon n'est pas supérieur à 85 % d'une distance de l'axe central à un point intermédiaire de l'arête périphérique supérieure, qui est équidistant des première et seconde extrémités distales supérieures.
35
10. Pôle magnétique selon l'une quelconque des revendications précédentes, le nombre, N, de secteurs de colline étant 3, 4, 5, 6, 7 ou 8, de préférence N = 4.
- 40 11. Cyclotron pour accélérer un faisceau de particules sur un trajet donné compris dans un espace, ledit cyclotron comprenant des premier et second pôles magnétiques selon l'une quelconque des revendications précédentes, les premier et second pôles magnétiques étant positionnés symétriquement par rapport à un plan médian perpendiculaire aux axes centraux des premier et second pôles magnétiques formant ledit espace, avec une partie d'espace de colline étant formée entre deux secteurs de colline opposés et des parties d'espace de vallée étant formées
45 entre deux secteurs de vallée opposés.
12. Cyclotron selon la revendication précédente, l'évidement ayant un premier et un second point distal d'évidement, lesdits premier et second points distaux d'évidement étant séparés l'un de l'autre par une distance L10, et la partie d'espace de colline entre une paire de secteurs de colline des premier et second pôles magnétiques ayant une
50 hauteur moyenne Gh, et le rapport Gh / L10 étant compris entre 5 et 100 %, de préférence entre 10 et 50 %, plus préférablement entre 20 et 33 %.
13. Cyclotron selon l'une quelconque des revendications 11 et 12, comprenant un point d'extraction, situé dans une partie d'espace de colline entre deux surfaces supérieures opposées de secteurs de colline des premier et second pôles magnétiques,
55
 - le trajet donné du faisceau de particules étant un trajet en spirale vers l'extérieur tournant autour de l'axe central jusqu'au premier point d'extraction, d'où le faisceau de particules peut être entraîné hors du cyclotron

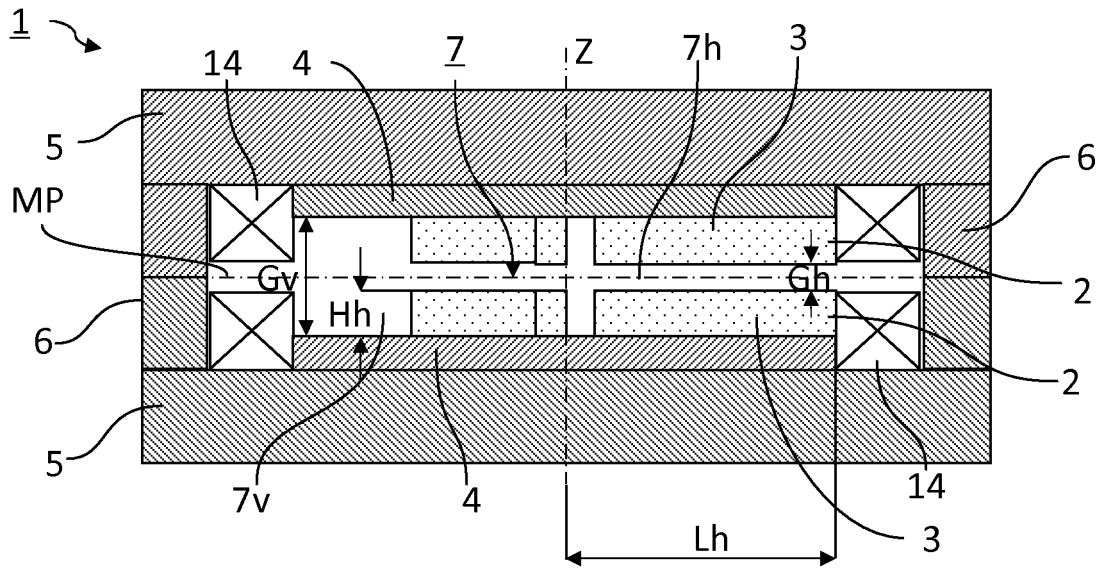
avec une énergie donnée le long d'un trajet d'extraction,

- l'évidement étant situé en aval dudit point d'extraction, l'aval étant défini par rapport à la direction du faisceau de particules, de telle sorte que

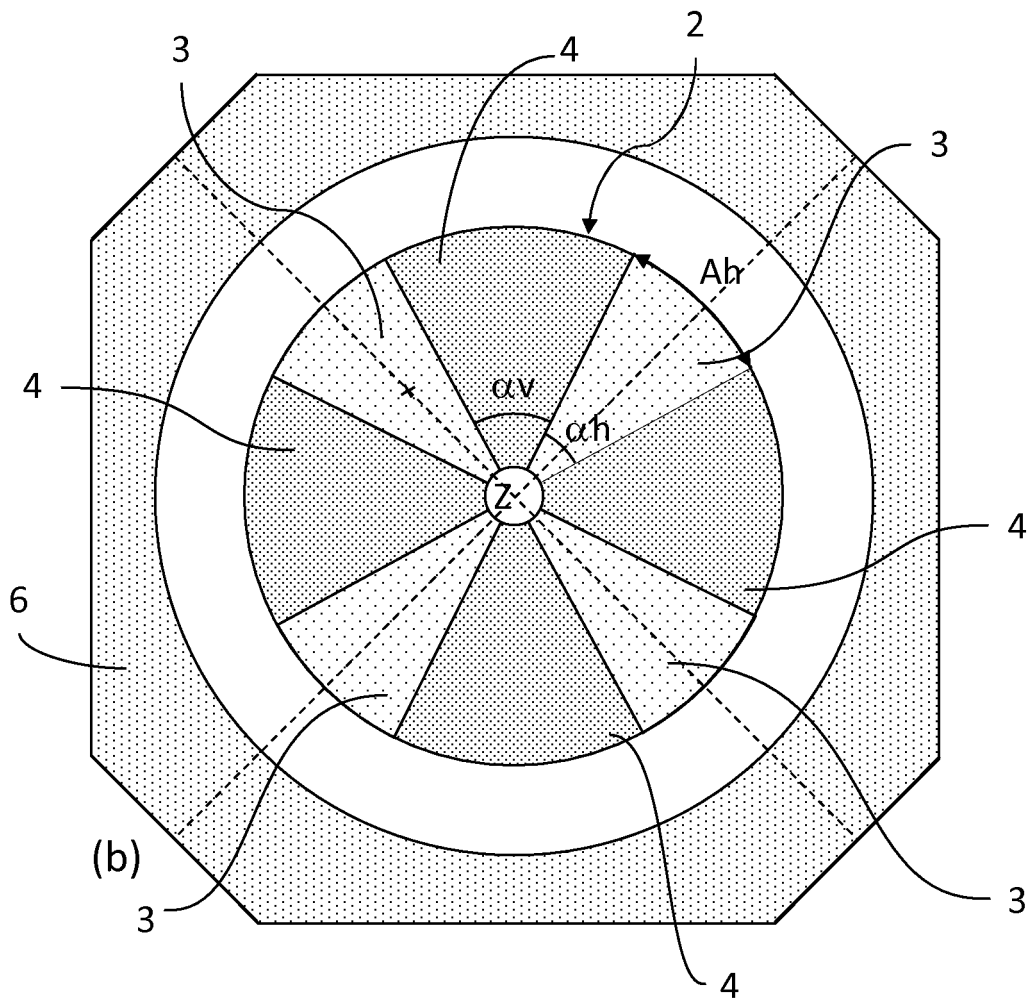
- le trajet d'extraction sort de la partie d'espace de colline correspondante en coupant l'évidement avec un angle compris entre 80 et 100°, de préférence entre 85 et 95°.

14. Cyclotron selon la revendication 13, comprenant un second point d'extraction dans un secteur de colline définissant un second trajet d'extraction, et comprenant un second évidement situé en aval du second point d'extraction, de sorte que le second trajet d'extraction sorte de la partie correspondante de l'espace de colline en coupant le second évidement avec un angle compris entre 80 et 100°, de préférence entre 85 et 95°.

15. Cyclotron selon la revendication 14, les premier et second points d'extraction étant situés sur une même partie d'espace de colline.



(a)



(b)

Fig. 1

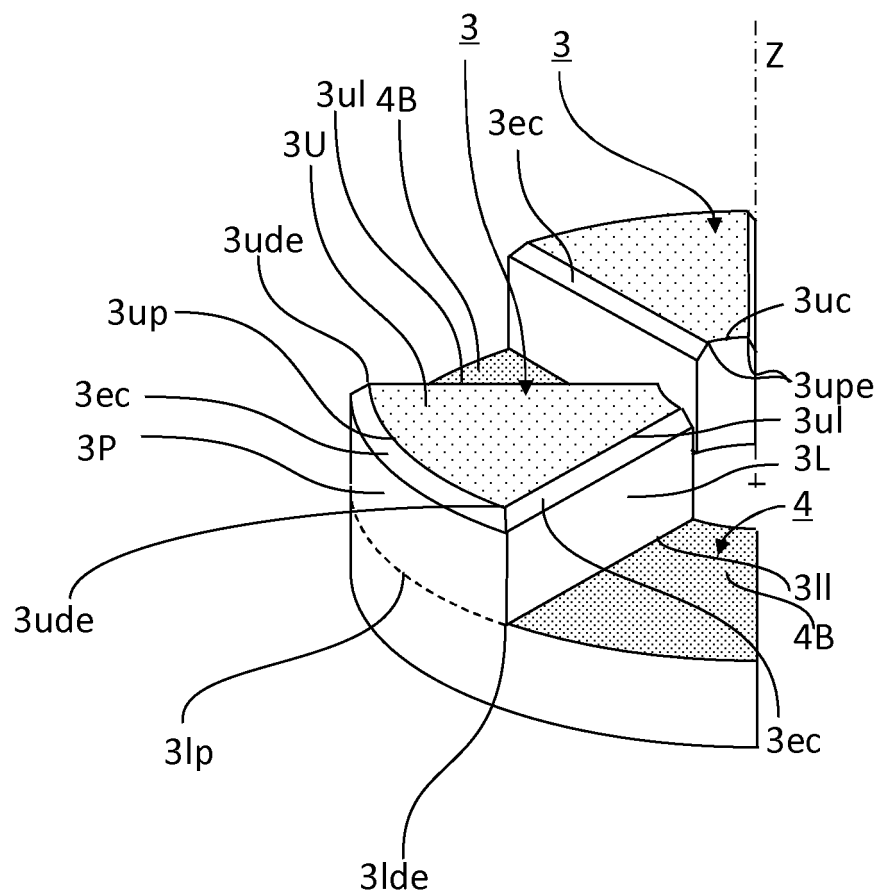


Fig. 2

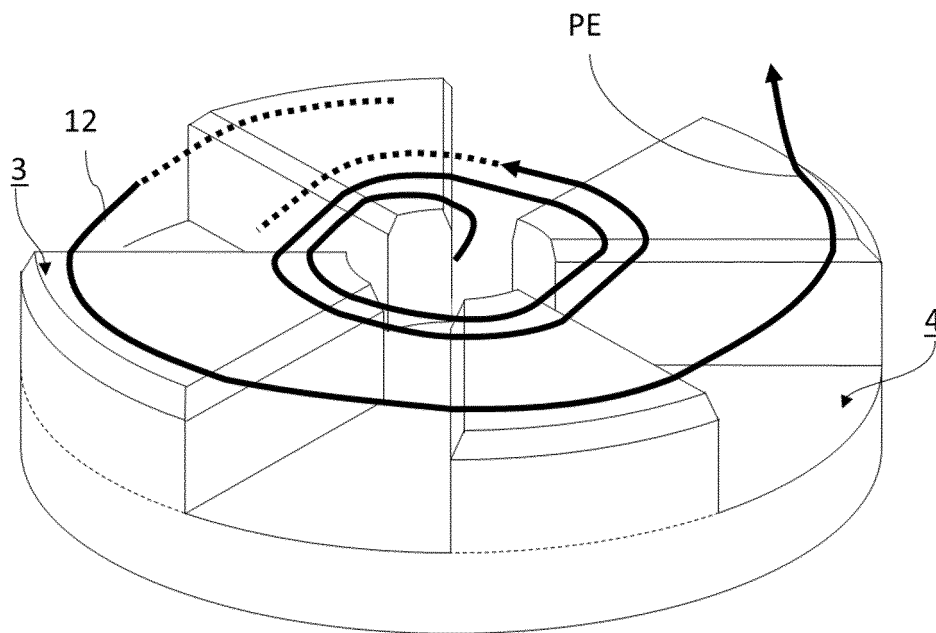


Fig. 3

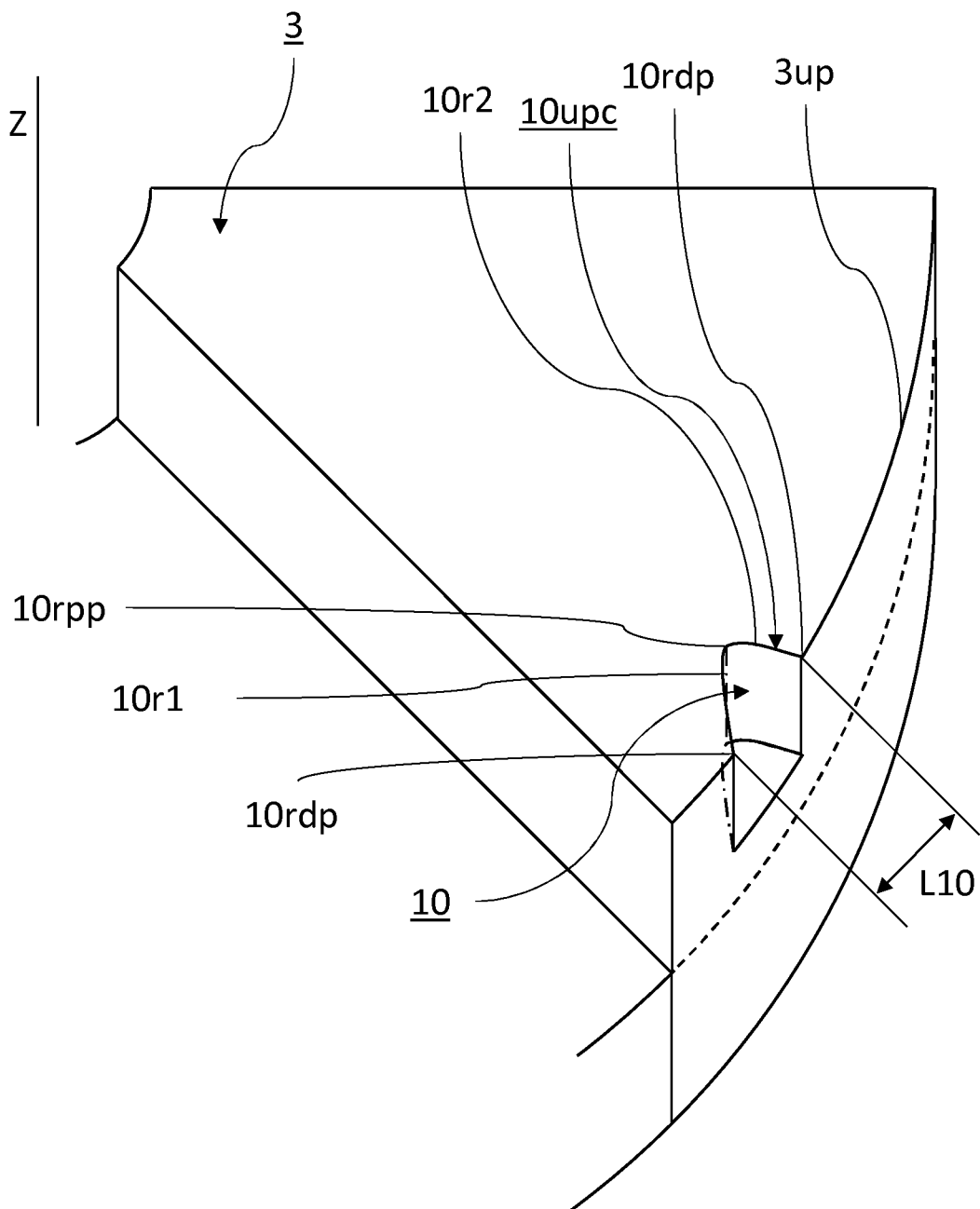


Fig. 4(a)

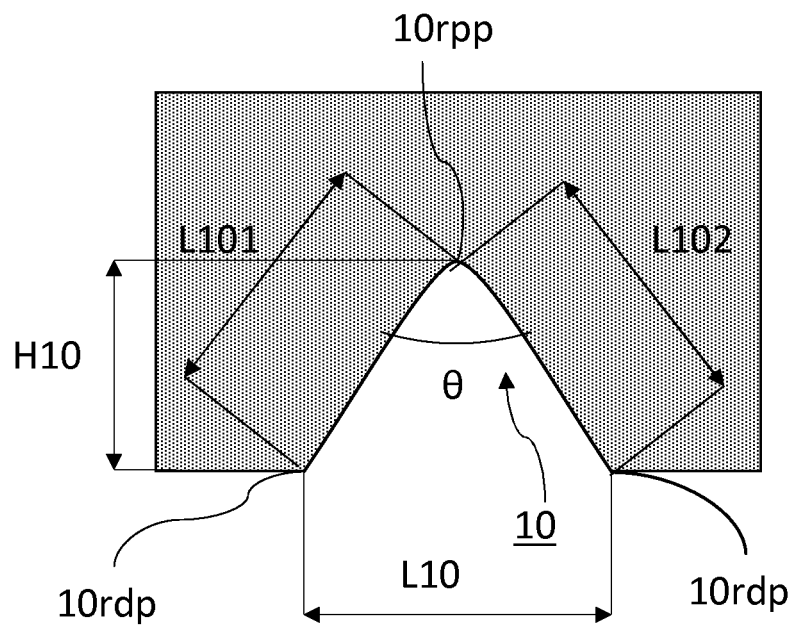


Fig. 4(b)

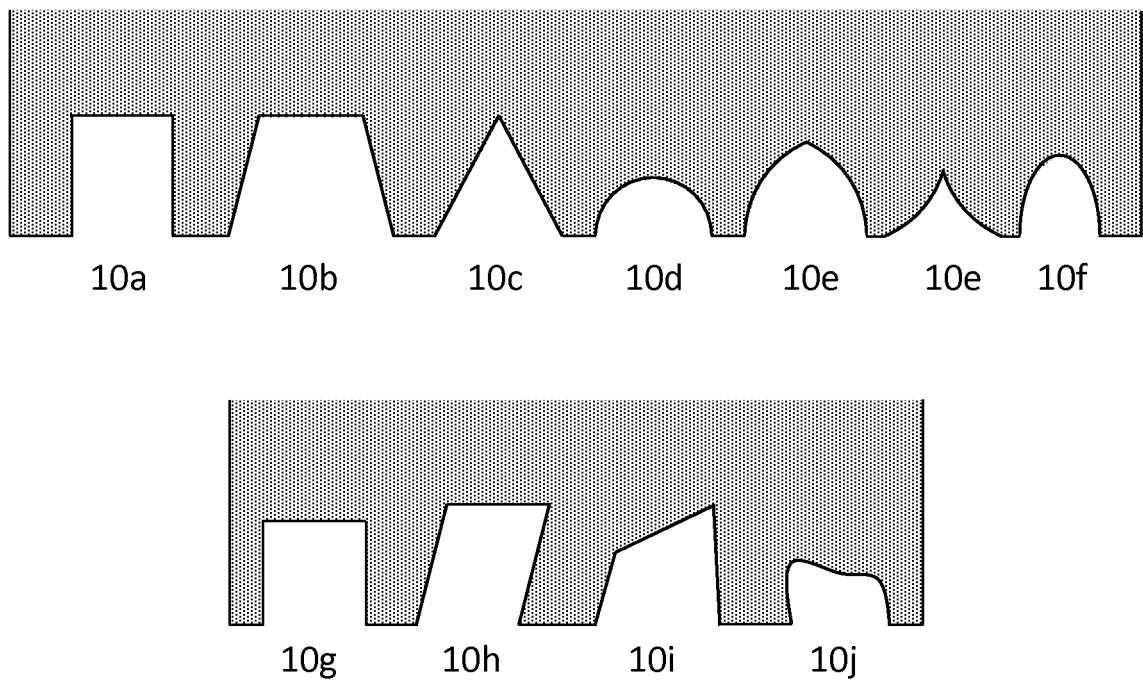
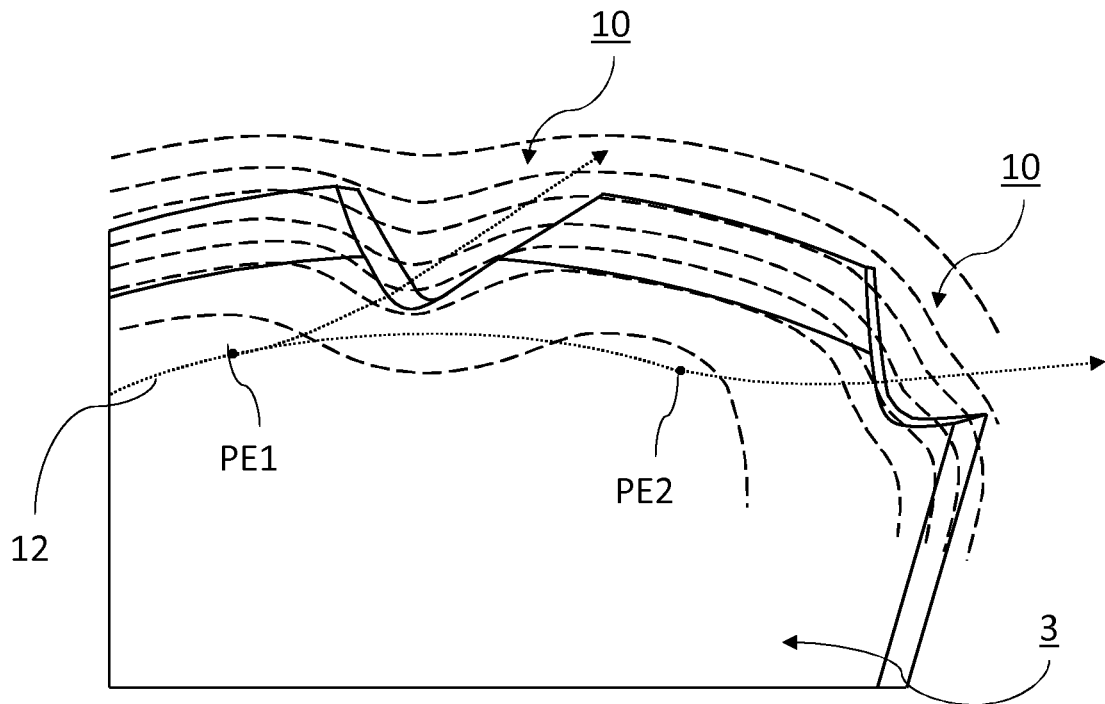
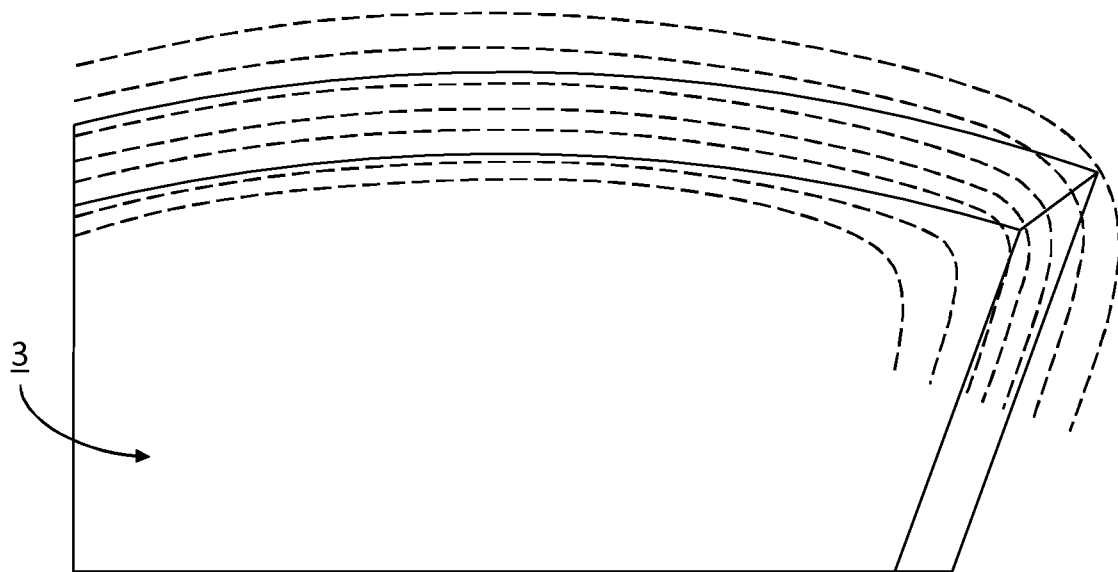


Fig. 6



(a)



(b)

Fig. 5

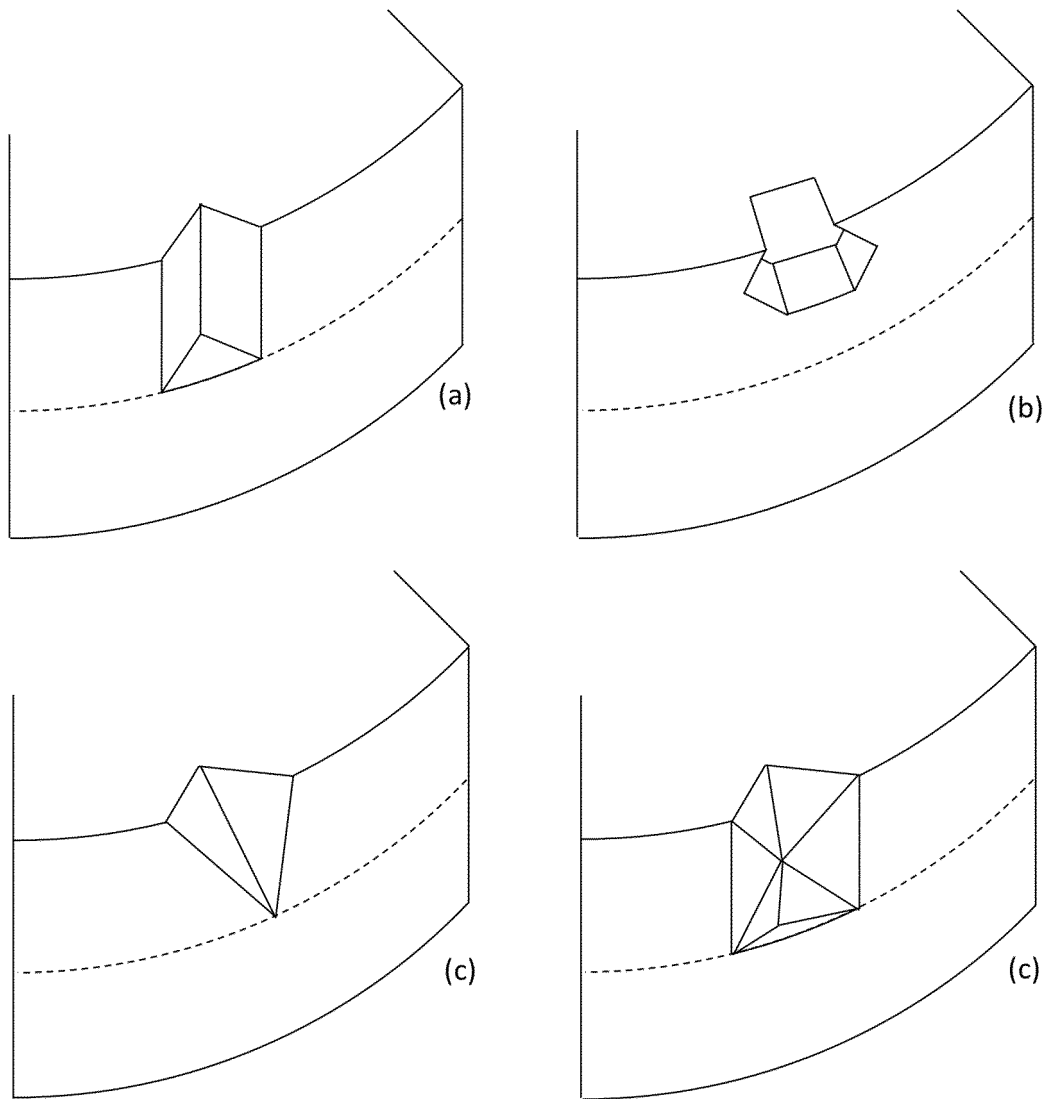


Fig. 7

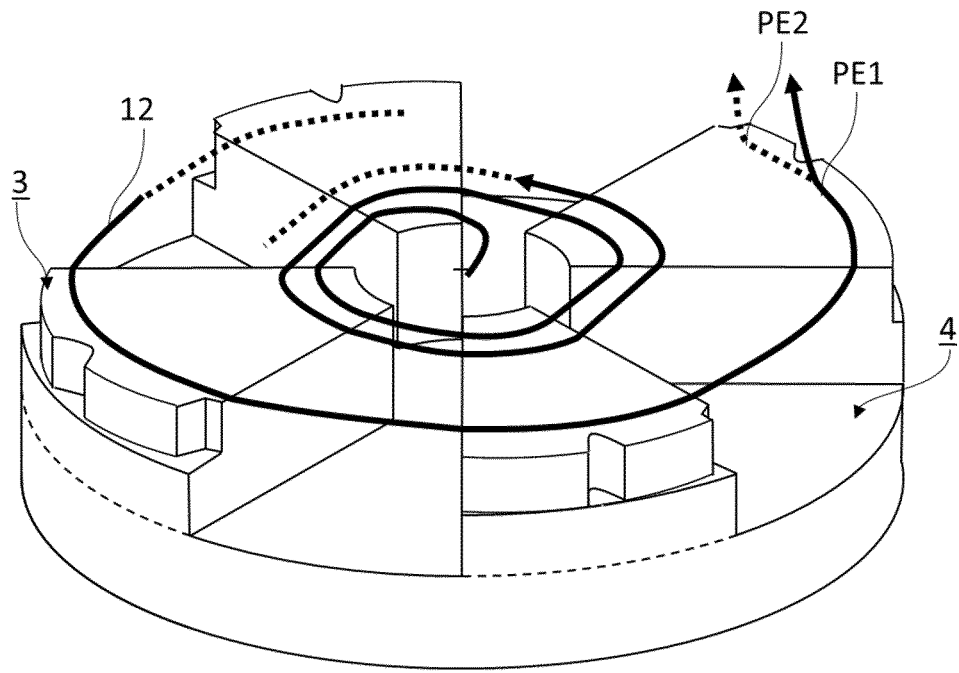


Fig. 8

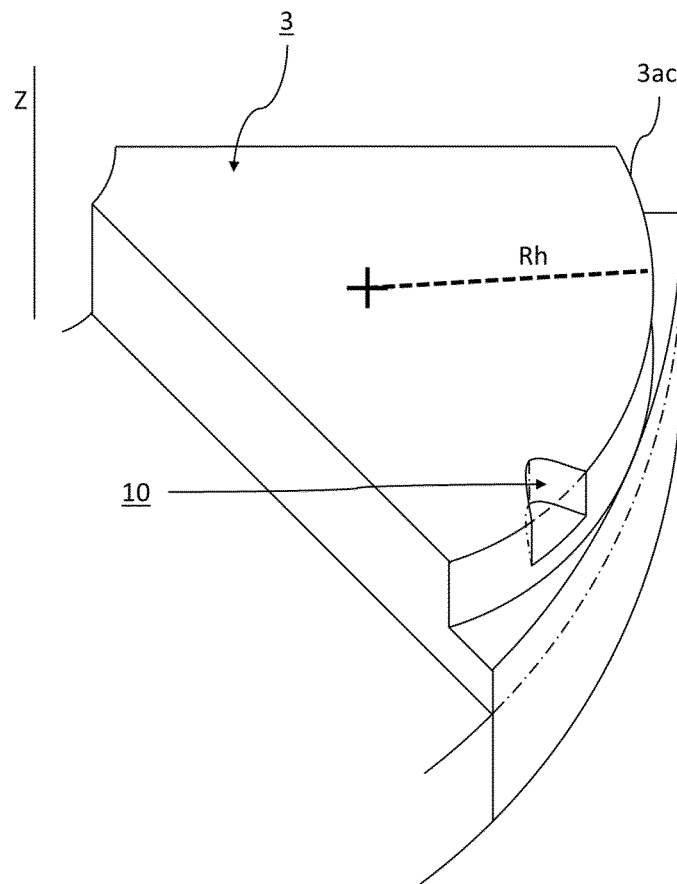


Fig. 9

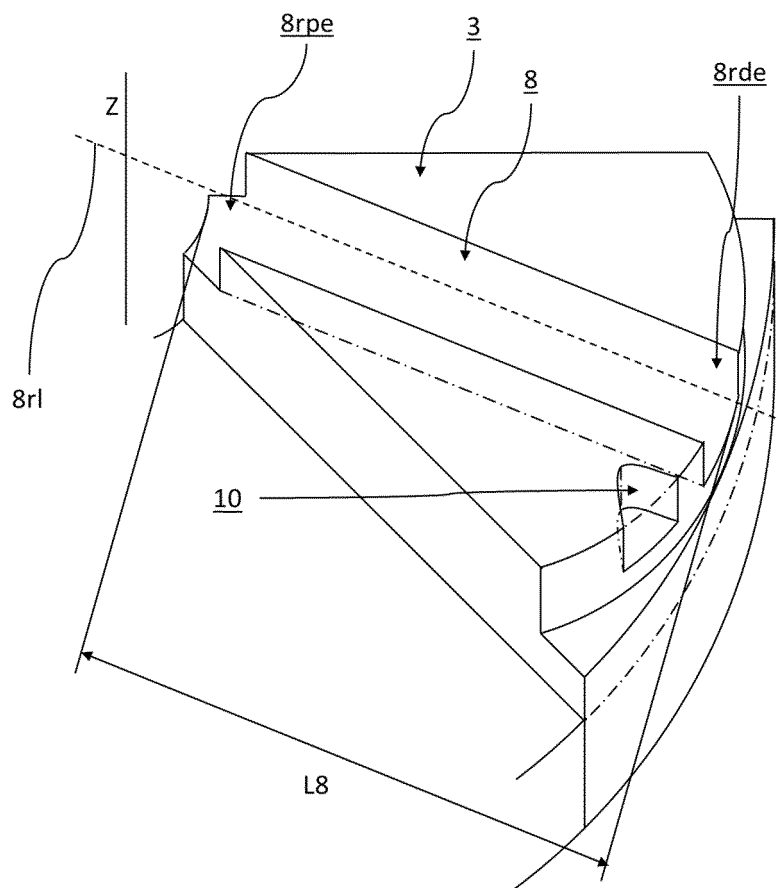


Fig. 10(a)

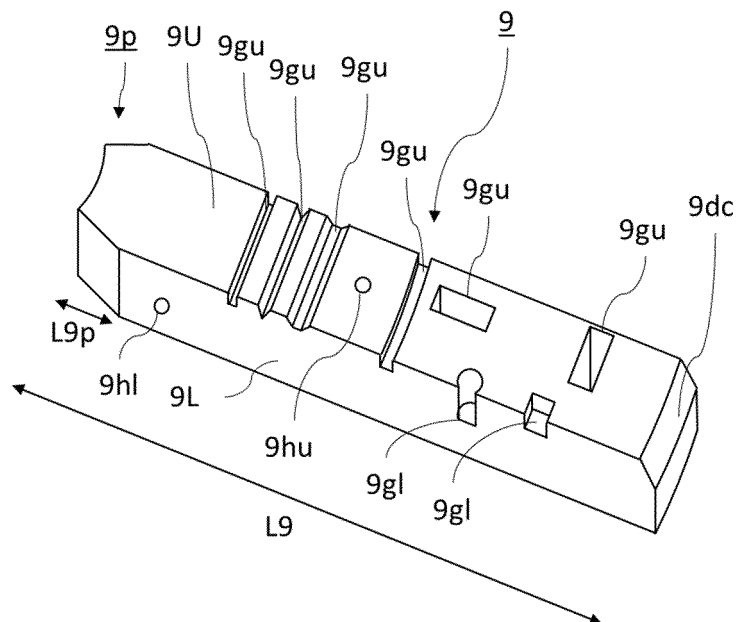


Fig. 10(b)

REFERENCES CITED IN THE DESCRIPTION

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