United States Patent

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[54] **ACCELERATOR TUBE ELECTRODE FOR FOCUSING A BEAM OF CHARGED PARTICLES**
15 Claims, 9 Drawing Figs.

[52] U.S. Cl. 250/49.5 C, 250/49.5 TE, 313/63, 313/82, 313/348
[51] Int. Cl. H01j 37/12, H01j 37/30
[50] Field of Search 313/63, 82, 86, 85, 348; 250/49.5 C, 49.5 TE

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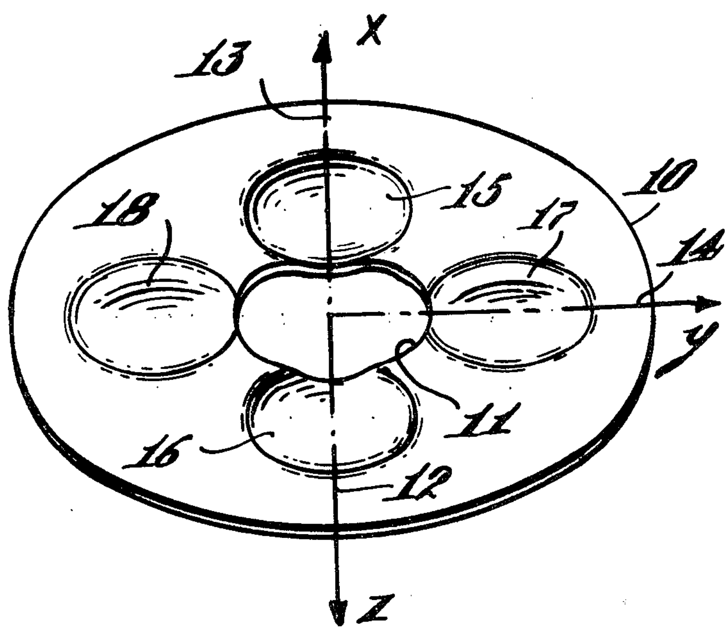
ABSTRACT: An electrode for use in an accelerator tube, which electrode provides for the focusing of a beam of charged particles within said tube as the particles travel along the length thereof. The electrode has a centrally located aperture and, symmetrically disposed about such aperture, an even number (at least four or more) of indentations, alternately projecting in opposite directions along the axis of the tube. The ideal shape of the electrode can be expressed mathematically as $z=f(r)\cos n\theta$ in a cylindrical coordinate system having coordinates r, θ, and z with the Z-axis corresponding to the direction of the tube axis. Here, $f(r)$ is a function which preferably should approximate $f(r)\approx kr^2$, for the region substantially immediately surrounding the aperture and, preferably, up to a radius of twice the aperture radius.



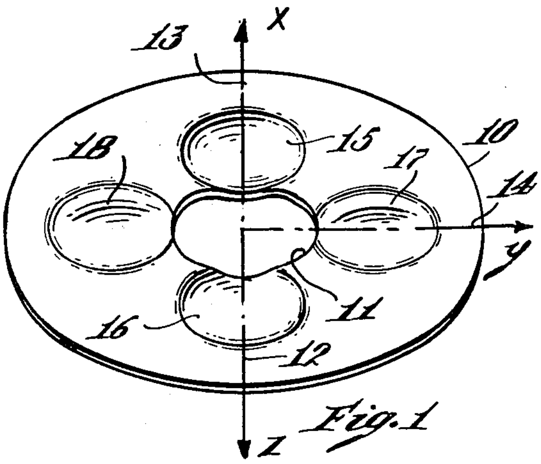


Fig. 1

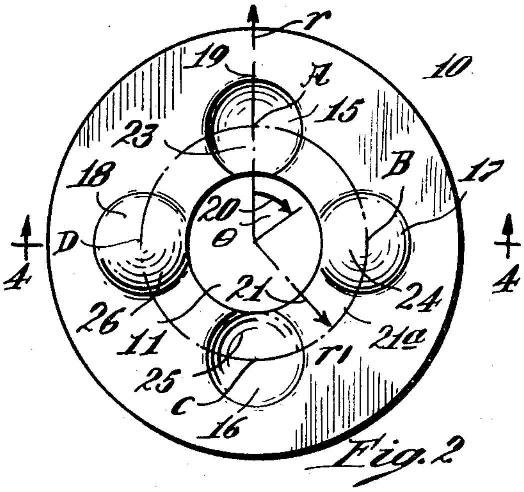


Fig. 2

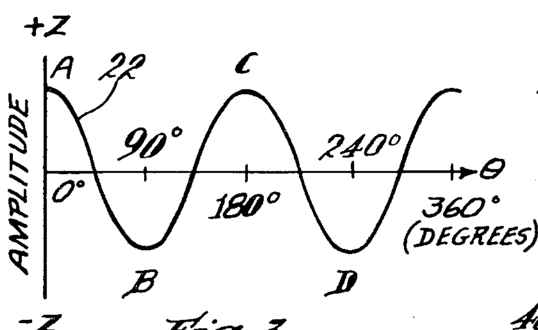


Fig. 3

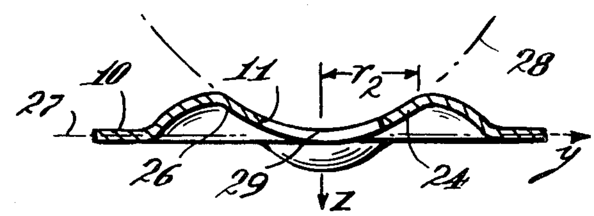


Fig. 4

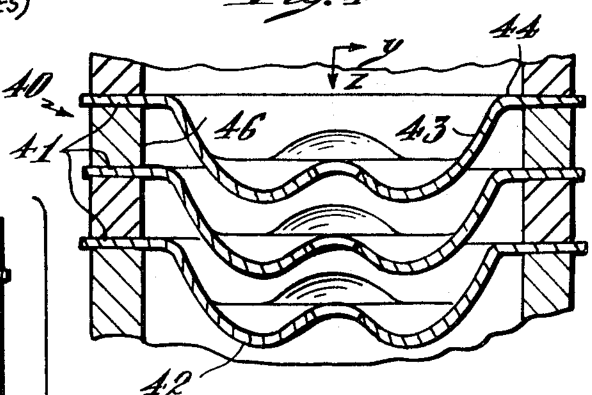


Fig. 7

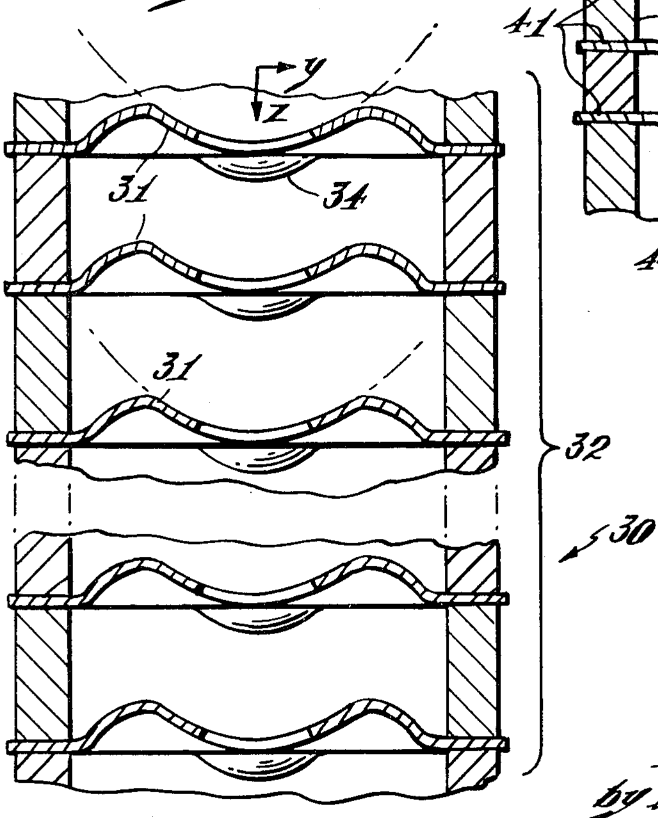


Fig. 5

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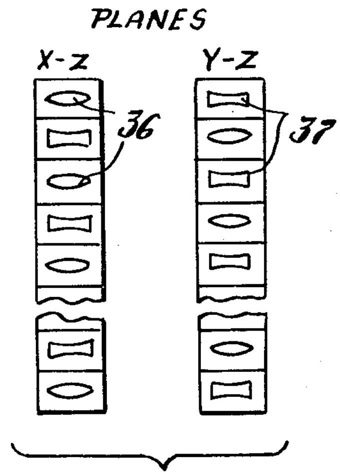

Fig. 6

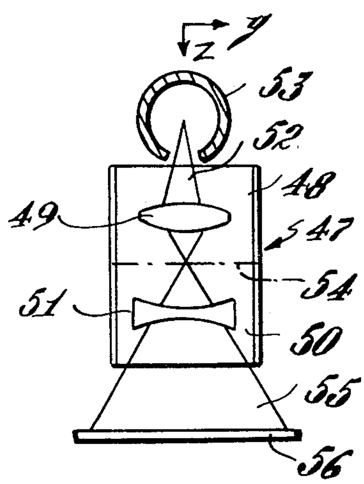

Fig. 8

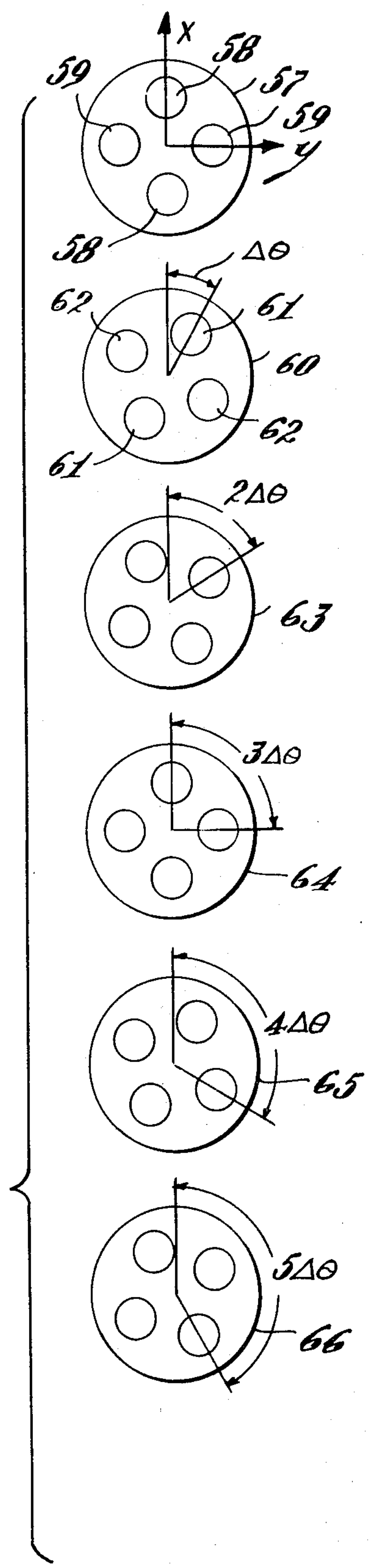

Fig. 9

ACCELERATOR TUBE ELECTRODE FOR FOCUSING A BEAM OF CHARGED PARTICLES

This invention relates generally to accelerator tubes and, more particularly, to electrodes for use therein.

In conventional accelerator tubes the structures thereof comprise a plurality of equipotential electrodes separated by relatively short, substantially cylindrical sections of insulator members made, for example, of glass, as is well known. Such electrodes normally each comprise a disk of conductive material, such as aluminum, having a centrally located aperture, the apertures of all of said electrodes being aligned so as to permit passage of charged particles down the tube therethrough. The charged particles are appropriately injected at one end of the tube and the tube has a suitable output utilization device for making use of the charged particles as they exit from the tube.

In some instances the electrodes are effectively cup shaped so as to shield the insulative inner surfaces of the tube located between the electrodes from bombardment by any free ions present in the tube which may be directed toward such surfaces as a result of their encounter with the charged particles being accelerated down the tube. If such bombardment is permitted to continue, an undesired charge, which cannot be appropriately drawn off, builds up on such surfaces to distort the accelerating field within the tube. By using substantially cup shaped electrode members, the inner surfaces of the insulator tube between electrodes are effectively shielded from such bombardment and any ions which are directed toward the inner surfaces of the tube are intercepted by the conductive member itself and charge buildup is prevented.

In any event, whether a flat disk or a cup-shaped disk electrode is utilized, very little focusing of the beam takes place in the tube itself other than in the fringing field at the entrance aperture, as is well known. In many instances, however, it is desirable to provide for such effective internal focusing of the beam of charged particles as the particles move downwardly through the tube, particularly in applications where it is desired to maintain a relatively narrow beam of particles throughout the tube. In tandem accelerator tubes, for example, especially in the high-energy portion thereof following the terminal stripper where inversion of the polarity of charge on the accelerated beam takes place, the beam tends to diverge appreciably as it travels further downward to the tube exit. The use of internal focusing of the beam along the tube prevents such beam diversion. Even in the upper portion of such a tandem tube, or in the tube of a single-stage accelerator, it may also be desirable to provide such internal focusing as as to keep the beam cross section small throughout the tube.

Further, in some beam processing operations, as described later, it may be desirable to provide strong defocusing of the beam close to the exit of the accelerator tube to produce an accelerated output beam having a flared shape, which beam can be used to bombard the materials to be processed. Such a system then can be utilized to replace more complicated scanning apparatus now available for such purposes, as explained more fully below.

In prior art single-stage tubes, the beam is generally caused to converge to an image, or waist, beyond the exit of the tube by virtue of the focusing power of the entrance aperture in combination with one or more lenses in the ion source or electron gun. The focal length, f, of the entrance-aperture lens is approximately

$f=4V/E$ (1) where E is the accelerating axial electric field in the tube and V is the injection voltage, i.e., the potential drop through which the particle has traveled before reaching the entrance aperture. The focal length is varied by varying the injection voltage V. In tandem accelerators a waist can be produced at the stripper in the terminal in the same way as explained above for single-stage accelerators. However, there is virtually no internal focusing in the second stage of prior art accelerators. The beam cross section at the exit is generally 2–4 cm. in diameter and diverging. External

focusing must be provided in the form of electric or magnetic lenses, generally quadrupole lenses.

In this invention internal focusing is provided by appropriately shaping the electrodes within the accelerator tube so that a set of such electrodes effectively acts as either a diverging or a converging lens in a specified plane with respect to the direction of travel of the charged particles therethrough. In a preferred embodiment thereof, such lens action is produced essentially by providing each conductive electrode of any particular converging or diverging set thereof with a group of four protrusions, two of which protrude from the principal plane of the electrode in the direction of travel of the particles and two of which protrude from the principal plane of the electrode in the opposite direction. More particularly, in a preferred embodiment, the electrode is shaped so that the locii of points (i.e., the displacement of the electrode surface from the principal plane thereof) at fixed radial distances from the center of the centrally located aperture of the electrode varies in a sinusoidal fashion with an amplitude substantially proportional to the square of the radial distance value, at least so long as such radial distance is less than an appropriately selected value. Thus, the sinusoidal relationship which is so chosen produces a first pair of positive protrusions in the electrode (i.e., displacements along the direction of travel of the particles) which are oppositely disposed from each other with reference to the aperture and a second pair of negative protrusions in the electrode (i.e., displacements in a direction opposite to such direction of travel) which are also oppositely disposed from each other with reference to the aperture and which are located intermediate the first pair of positive protrusions. Thus, said protrusions are arranged essentially symmetrically about the aperture. The set of electrodes then acts in specified planes as either a converging or a diverging lens depending on the orientation of such protrusions relative to such planes, as described more fully below.

The invention can be more easily understood with the assistance of the accompanying drawings wherein:

FIG. 1 shows a perspective view of a typical electrode structure fabricated in accordance with the invention and which may be used in an accelerator tube;

FIG. 2 shows a plan view looking downwardly at the electrode of FIG. 1;

FIG. 3 shows a curve representative of the locii of points on the surface of the electrode structure of FIG. 1 at a fixed radial distance from the center thereof;

FIG. 4 shows a view in cross section taken along the lines 4—4 of the electrode depicted in FIG. 2;

FIG. 5 shows a view in cross section of a portion of an accelerator tube utilizing a set of electrodes of FIG. 1 oriented to provide focusing in the x–z plane and defocusing in the y–z plane;

FIG. 6 shows two diagrammatic views of the converging and diverging effects in an accelerator tube using the electrode configuration of the invention;

FIG. 7 shows a view in cross section of a portion of an accelerator tube using cup-shaped embodiments of a set of electrodes of the invention oriented to provide focusing in the y–z plane and defocusing in the x–z plane;

FIG. 8 shows a diagrammatic view of an accelerator tube using sets of the electrode configuration of the invention in a system for producing a flared accelerated beam of charged particles; and

FIG. 9 shows diagrammatic plan views of a further embodiment of the invention depicting the orientation of a plurality of successive electrodes of the invention as used in an accelerator tube for producing a spiraled focusing effect.

In FIG. 1, which shows a perspective view of an electrode fabricated in accordance with the invention, the electrode comprises a substantially circular conductive member **10**, fabricated of aluminum for example, having a centrally located aperture **11**. If the electrode structure is considered with reference to a linear coordinate system having x, y, and z-axes and its origin at the center of aperture **11**, the beam of charged particles can be represented as passing through aperture **11** downwardly in the positive *z*-direction indicated by the axis **12**, as shown in the figure. The orthogonal directions *x* and *y* perpendicular to the *z* direction are shown by axes **13** and **14** and the *x–y* plane is hereinafter referred to as the principal plane of the electrode. The conductive member **10** has a first pair of protrusions **15** and **16** projecting downwardly in the positive *z*-axis direction and lying on opposite sides of center aperture **11** along the *x*-axis direction. Further, conductive member **10** has a second pair of protrusions **17** and **18** projecting upwardly in in the negative *z*-axis direction, as shown, and lying on opposite sides of center aperture **11** along the *y*-axis direction.

The plan view of electrode **10** looking downwardly in FIG. **2** also can be considered with reference to a cylindrical coordinate system having its origin at the center of aperture **11** and having its radial coordinate *r* indicated by dashed line **19**, its angular coordinate θ indicated by angle **20**, both in the plane of the drawing, and a linear coordinate *z* (not specifically shown) which extends in a positive direction into the paper.

With reference to FIG. **2**, the surface of electrode **10** is so shaped that, if a cylindrical cut is made at a radial distance r_1 from the center of aperture **11**, indicated by the radial line **21**, the locii of points in the *z*-direction at the surface of electrode **10** along dashed line **21***a* is sinusoidal in shape and has an amplitude substantially proportional to r_1^2. The curve representing such locii is shown as curve **22** in FIG. **3** wherein the points A, B, C and D coincide with the corresponding points shown in FIG. **2**. Thus, the displacement, Δz, of the surface of electrode **10** in the *z*-direction, as represented by curve **22**, can be defined in the cylindrical coordinate system by the following equation:

$$\Delta z = kr^2 \cos 2\theta \qquad (2)$$

where *k* is a constant and *r* and θ are as defined above.

In order to provide the desired converging (focusing) or diverging (defocusing) lens action, as explained more fully below, it is necessary that the shape of the curve shown in FIG. **3** be maintained for radial distances up to a preselected value so that the surfaces **23**, **24**, **25** and **26** of protrusions **15**, **17**, **16**, and **18**, respectively, adjacent aperture **11** conform to Equation (2) above. Beyond such specified radial distance, the influence on the field in the space where the particles are moving becomes less significant and the shape accordingly less important. For most practical applications, conformity should be maintained, for example, up to a value of *r* which is of the order of magnitude of twice the radius of the center aperture **11**.

FIG. **4**, a cross-sectional view taken along the lines **4—4** of FIG. **2** (i.e., a view in the *y–z* plane), provides another viewpoint for expressing the desired shape of the protruding surfaces involved with reference to an *x–y–z* coordinate system. For example, as shown therein, the electrode has a principal plane shown by dashed line **27** and surfaces **24** and **26** displaced therefrom conform to a selected portion of a parabolic curve, denoted by dashed line **28** in the *y–z* plane, which curve has its apex **29** substantially at the center of the aperture **11**, as shown. Thus, in the *y–z* plane the parabolic shape shown is maintained for a distance r_2 and thereafter departs from such paraboidal shape. A similar conformity exits with reference to the protruding shapes in the *x–z* plane.

FIG. **5** shows a portion of a section of an accelerator tube **30** which utilizes electrodes in accordance with the invention to provide a desired lens operation. To achieve a desired converging or diverging lens effect, a plurality of successive adjacent electrodes, identically oriented with respect to each other in any given converging or diverging section of the tube, are used. Thus, to produce a focusing effect in the *x–z* plane and a defocusing effect in the *y–z* plane, a set of such electrodes **31** in a section **32** of the tube are oriented in the manner shown in FIG. **5** with their positive protrusions (i.e., in the positive *z*-direction) on the *x*-axis and their negative protrusions (i.e., in the negative *z*-direction) on the *y*-axis. Such a section of the tube, of which only a portion is shown in FIG. **5**, may contain, for example, as many as 10, 20 or 30 identically oriented electrodes, or even more, the number depending upon the electrode spacing, the total length of the tube, and upon what focusing properties are desired. Alternatively in order to achieve a focusing effect in the *y–z* plane and defocusing effect in the *x–z* plane, the electrodes of such a section are oriented orthogonally with respect to the electrodes **31** shown in FIG. **5** with their positive protrusions on the *y*-axis and their negative protrusions on the *x*-axis.

FIG. **6** shows two simplified diagrammatic views of an accelerator tube consisting of a number of such converging or diverging sections, alternately focusing and defocusing the charged particle beam in given planes, as shown by the exemplary analogous converging and diverging lenses **36** and **37**, respectively. As is well known in beam optics the net effect of such an arrangement of alternately focusing and defocusing elements is to provide an overall focusing, i.e., a diverging beam will be made to converge again. Depending upon the strength of the focusing effect there may actually be several beam crossovers or waists within the length of the tube. Such operation, for example, may be considered analogous to the focusing effect in an alternating gradient synchrotron.

Although the sections are shown as alternating in FIG. **6**, it is clear that in some applications it may be desirable to place one or more sections, which produce substantially the same lens effect, adjacent one another along the tube length.

If the effect desired is to produce an image or waist at, or close to, the exit of the tube of a beam diverging from a point near the entrance thereof, the tube can be made of several conventional, nonfocusing sections at either end, with, for example, two or four sections utilizing sets of electrodes of the type disclosed by this invention, such sections being positioned at or near the middle of the tube. Other variations in the placement of converging, diverging, or nonfocusing sections of the tube may be used depending on the effects desired.

Although the electrodes shown as used in the tube of FIG. **5**, for example, are in some applications effective enough in the shape depicted to prevent a buildup of charge on the insulating inner surfaces of the accelerator tube, primarily because of the presence of the protrusions therein, in other applications it may be desirable to utilize the electrode structure of the invention in an effective cup-shape configuration. For example, FIG. **7** shows a cross-sectional view of such an arrangement wherein a portion of a section of an accelerator tube **40** utilizes a set of electrodes **41** each formed in a generally cup-shaped fashion having a bottom cup portion **42**, an upwardly extending portion **43**, and a flange portion **44** for suitable attachment to the tube as shown. The surfaces at the bottom cup portions **42** have protrusions of the type previously discussed above for producing the lens effects desired. In this case they are shown as having an orientation so that in the section, of which FIG. **7** shows only a portion, a diverging lens effect is produced in the *x–z* plane and a converging lens effect in the *y–z* plane. In such a configuration utilizing cup-shaped electrodes, prevention of a charge buildup on the inner surfaces **46** of tube **40** is more effectively assured.

FIG. **8** depicts an alternative embodiment of an accelerator tube structure utilizing the principles of the invention, wherein a tube **47** utilizes at its entrance end an upper section **48** having a set of identically oriented electrodes fabricated in accordance with the invention, which set effectively provides a converging lens effect in the *y–z* plane (shown) and a diverging lens effect in the *x–z* plane (not shown), as shown diagrammatically by the analogous lens **49** at the entrance end. Tube **47** further utilizes a lower section **50** having a set of identically oriented electrodes, which electrodes, however, are orthogonally oriented with respect to the set of electrodes in upper section **48** so as to provide a diverging lens effect in the *y–z* plane, with a corresponding converging effect in the *x–z* plane, at the exit end of tube **47** as shown diagrammatically by the analogous lens **51**. In this configuration, a flared beam **52** of charged particles (which particles are injected at the entrance end through an appropriately slotted entrance member 53) is focused in the y–z plane by converging section 48 at an internal focal plane represented by reference numeral 54 as shown and, thence, diverges with the divergence enhanced by section 50 so as to produce at the exit end of the tube an accelerated flared beam 55 in the y–z plane, which beam can be used in an appropriate beam processing system. Thus, a material 56 which is to be processed by the accelerated particles can be appropriately passed under the flared particle beam 55 which is produced at the exit end of the tube. Such a system can be used, for example, as a substitute for a conventional beam scanning system wherein an accelerator tube produces an effective pencil beam which must be appropriately oscillated to produce a fanned scanning effect in a beam bombardment process. The embodiment of FIG. 8 using the principles of the invention eliminates the necessity for an oscillating beam system and effectively produces a fixed flared beam which is more easily obtained and made available for such processing.

To understand the operation of the invention more clearly, the equation for the scalar potential Φ in a tube section which is to act as an effective internal quadrupole lens, as well as to accelerate particles, can be written in the x–y–z coordinate system as:

$$\Phi = -Ez + G/2(x^2 - y^2) \qquad (3)$$

where E is the electric field strength in the axial direction of the tube and G is the gradient of the quadrupole. For positively charged particles the electric field will have one polarity, while for negatively charged particles the electric field polarity will accordingly be reversed. Since on an equipotential surface the rate of change of the potential (i.e., $\Delta\Phi$) is zero, the rate of change of the surface dimension in the z-direction (i.e., Δz) can be expressed as follows:

$$\Delta z = (G/2E)\,(x^2 - y^2) \qquad (4)$$

Thus, the above equation (4) can be written in a cylindrical coordinate system, wherein $x = r\cos\theta$ and $y = r\sin\theta$, to correspond to the form of equation (2) above. Thus, as can be seen by equation (2), the rate of change in the z-direction is proportional to the square of the radial distance r and is sinusoidal in shape as expressed by the term $\cos 2\theta$ of such equation. By comparing equation (2) and (4) one sees that the gradient G can be expressed in terms of E and the geometry parameter k as

$$G = 2kE \qquad (5)$$

Although the preferred embodiments shown in FIG. 1, for example, provide a quadrupole lens effect by utilizing four symmetrically disposed protrusions as shown therein, it may be desirable in some applications to use more protrusions, in even numbers, again symmetrically disposed about the central aperture. For example, six or eight protrusions for producing sextupole or octopole lens effects may be used. In such case the expression for Δz may be more generally expressed as:

$$\Delta z = kr^n \cos n\theta \qquad (6)$$

In the particular preferred embodiments discussed above each tube section, which uses a set of identically oriented electrodes made in accordance with the invention, is arranged so that such electrode set is orthogonally oriented with respect to the electrode set of adjacent sections of the tube so that alternating converging-diverging combinations are achieved. However, it may be desirable in some instances to arrange the electrodes within the tube so that each single successive electrode is oriented at a fixed angle, less than 90°, relative to its adjacent preceding electrode. Thus, for example, as shown diagrammatically in the plan views of FIG. 9, a first single electrode 57 of the type shown in FIG. 1, and merely depicted diagrammatically in the drawing, has an orientation such that its protrusions 58 in the negative z-direction lie along the x-axis and its protrusions 59 in the positive z-direction lie along the y-axis, as shown. The next adjacent electrode 60 is oriented so that its negative protrusions 61 (and its positive protrusions 62) lie at a fixed angle, $\Delta\theta$, with reference to the corresponding protrusions of electrode 57. Each successive electrode is thereupon rotated through the same fixed angle $\Delta\theta$ with respect to its adjacent preceding electrode, as shown by subsequent electrodes 63–66, with still further electrodes (not shown) continuing the same sequence along the length of the tube. Accordingly, in such an arrangement, an effective spiraled focusing effect of the charged particle beam can be achieved, if desired.

What is claimed is:

1. An electrode for use in an accelerator tube, said electrode comprising
   - a conductive member adapted to be attached to said tube and having a centrally located aperture for permitting the passage of charged particles therethrough;
   - said conductive member being shaped such that the displacement of the surface thereof from the principal plane of said conductive member at fixed radial distances from the center of said aperture varies sinusoidally and has amplitudes which vary as an increasing function of the value of said radial distance when said radial distance is less than a preselected value.

2. An electrode in accordance with claim 1 wherein said sinusoidal variation is such that said displacement in a full circle about said aperture is equivalent to two or more wavelengths and the amplitude of said displacement varies substantially as the square of the value of said radial distance when said radial distance is less than said preselected value.

3. An electrode in accordance with claim 2 wherein said displacement is equivalent to two wavelengths and said preselected value is approximately twice the value of the radius of said centrally located aperture.

4. An electrode in accordance with claim 1 wherein said displacement can be expressed in a cylindrical coordinate system having its origin at the center of said aperture substantially by the expression

$$\Delta z = kr^2 \cos n\theta$$

wherein r is the radial distance from said center, θ is the angular position about said center, k is a constant, n is a whole number greater than one, and Δz is the displacement in a direction substantially parallel to the direction of travel of said particles.

5. An electrode in accordance with claim 1 wherein said displacement is such as to form
   - a first pair of protrusions being oppositely disposed with respect to said aperture and protruding in the direction of travel of said particles; and
   - a second pair of protrusions intermediate said first pair of protrusions, said second pair of protrusions being oppositely disposed with respect to said aperture and protruding in a direction opposite to the direction of travel of said particles.

6. An electrode in accordance with claim 5 wherein said first and said second pairs of protrusions are symmetrically disposed about said aperture.

7. An electrode in accordance with claim 1 wherein said electrode is formed in a cup-shaped configuration.

8. An accelerator tube for accelerating charged particles passing therethrough, said tube utilizing electrodes in accordance with claim 1, wherein said tube comprises
   - one or more first sections, each said first sections including a set of said electrodes substantially identically oriented with respect to each other for producing a converging lens effect with respect to said charged particles in a first plane and a diverging lens effect with respect to said charged particles in a second plane; and
   - one or more second sections, each said second sections including a set of electrodes substantially orthogonally oriented with respect to the set of electrodes of said first sections for producing a diverging lens effect with respect to said charged particles in said first plane and a converging lens effect in said second plane with respect to said charged particles;
   - said electrodes in each said first and said second sections being spaced at specified distances from each other to form a plurality of spaced equipotential surfaces along the length of said tube.

9. An accelerator tube in accordance with claim 8 wherein said first and said second sections are alternately positioned along the length of said tube.

10. An accelerator tube in accordance with claim 8 and further including one or more further sections, each said further section including a set of electrodes which produce substantially no converging or diverging lens effects in either said first or said second planes.

11. An accelerator tube in accordance with claim 10 wherein said further sections are positioned at the entrance and exit end portions of said tube and said first and second sections are positioned in the central portion of said tube.

12. An accelerator tube utilizing electrodes in accordance with claim 1 wherein said electrodes are positioned along the length of said tube and each successive electrode is oriented at an angle less than 90° from its adjacent preceding electrode.

13. An accelerator tube in accordance with claim 12 wherein said angles between each adjacent pairs of said electrodes are equal.

14. A system for accelerating charged particles utilizing an accelerator tube in accordance with claim 8 wherein said accelerator tube comprises

one said first section mounted at or near the entrance end of said tube to produce a converging lens effect with respect to said charged particles in a first plane and a diverging lens effect with respect to said charged particles in a second plane; and

one said second section mounted at or near the exit end of said tube to produce a diverging lens effect with respect to said charged particles in said first plane and a converging lens effect in said second plane;

said system further includes

a source mounted at the entrance end of said tube for providing a flared input beam of charged particles;

whereby an accelerated output flared beam of said charged particles is produced at the exit of said accelerator tube.

15. A processing system utilizing an accelerating system in accordance with claim 14 and further including

means for supplying material to be processed by the impingement of charged particles thereon; and

means for moving said processing material into the path of said output flared beam of charged particles whereby said material is processed by the impingement of said charged particles thereon.

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