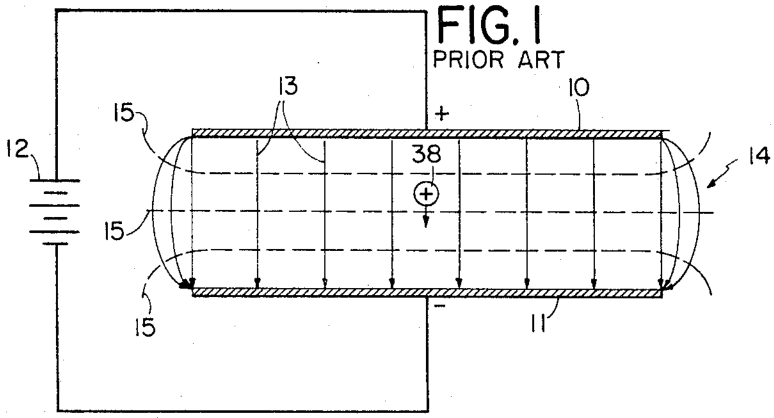
Oct. 22, 1968 E. E. HAND 3,407,323

ELECTRODE STRUCTURE FOR A CHARGED PARTICLE ACCELERATING APPARATUS, ARRAYED AND BIASED TO PRODUCE AN ELECTRIC FIELD BETWEEN AND PARALLEL TO THE ELECTRODES

Filed May 23, 1966 4 Sheets-Sheet 1

FIG. 1
PRIOR ART



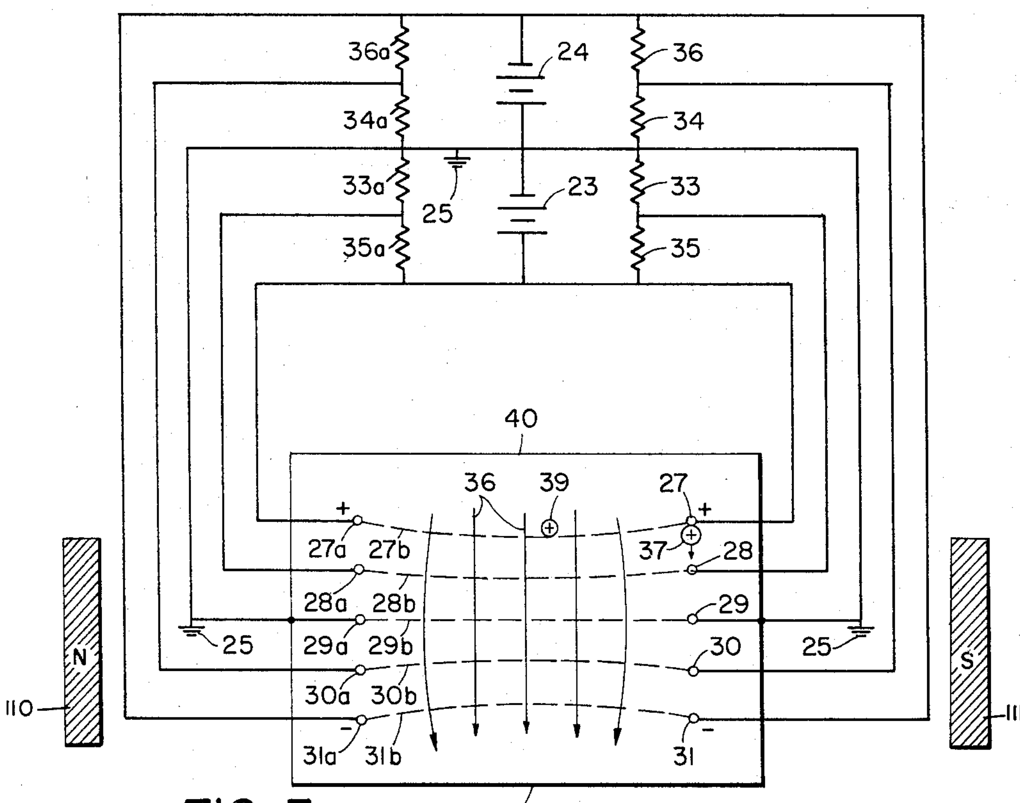


FIG. 3

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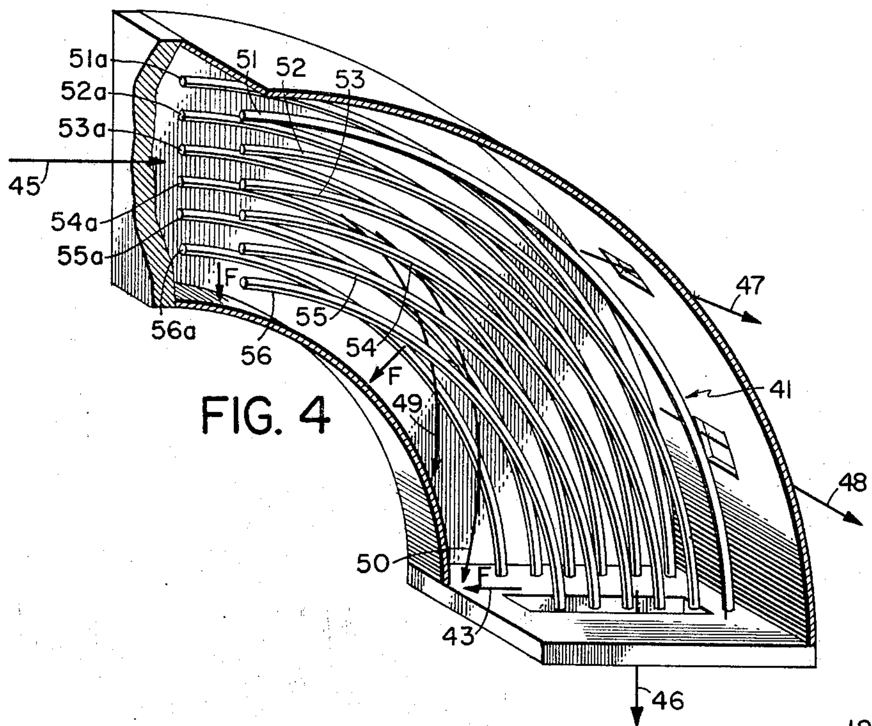

FIG. 4

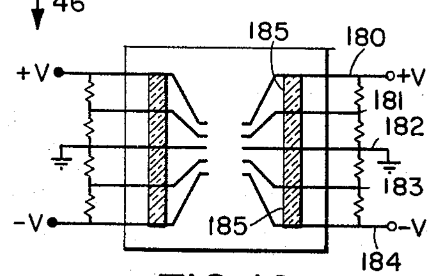

FIG. 10

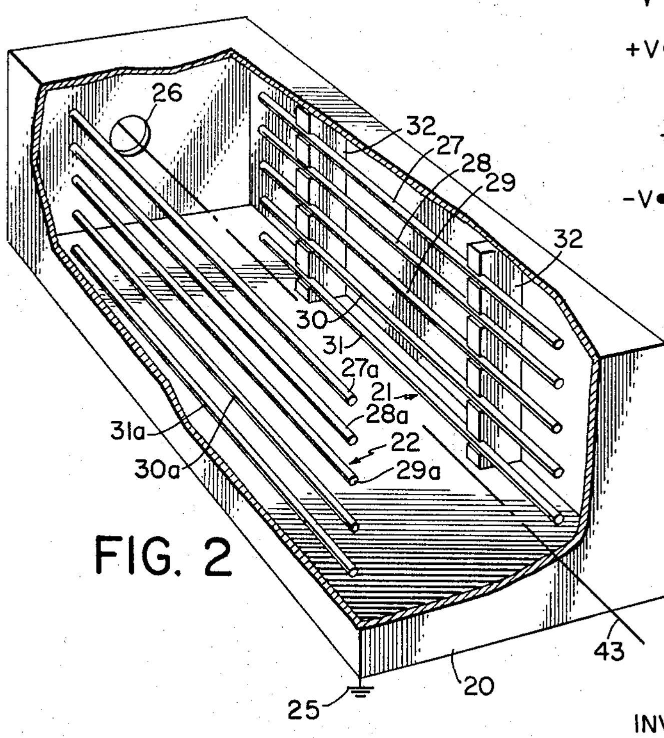

FIG. 2

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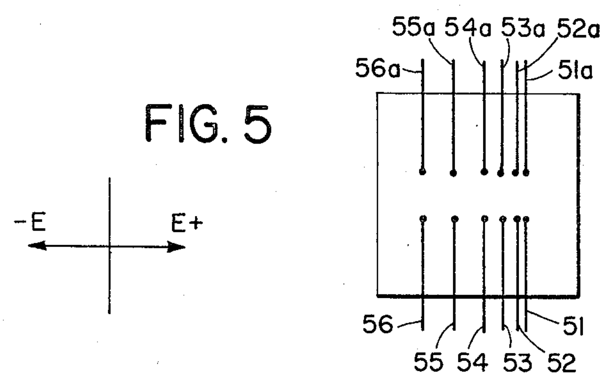
FIG. 5



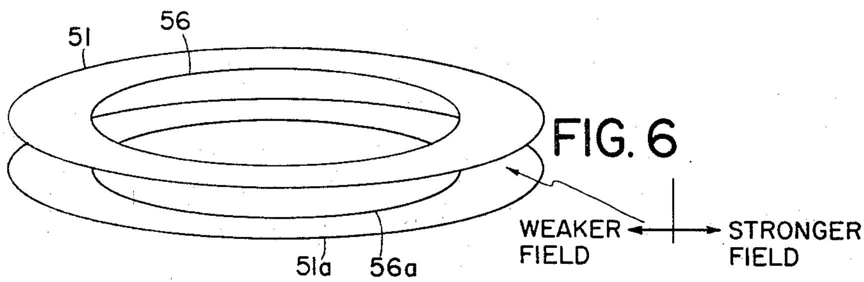
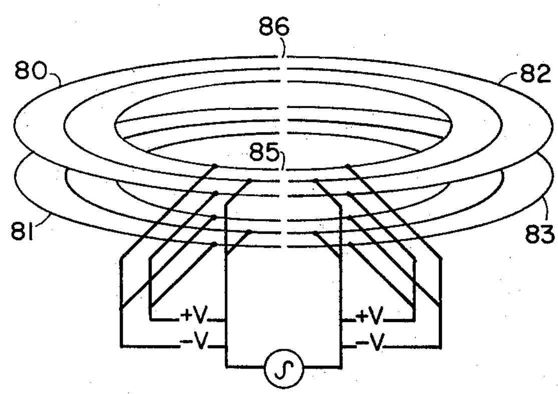


FIG. 6

FIG. 8



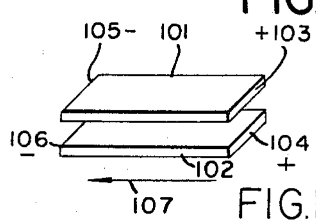


FIG.12

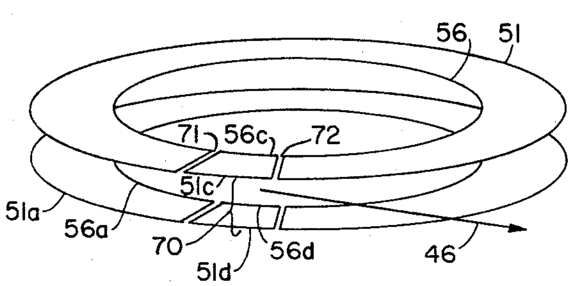


FIG. 7

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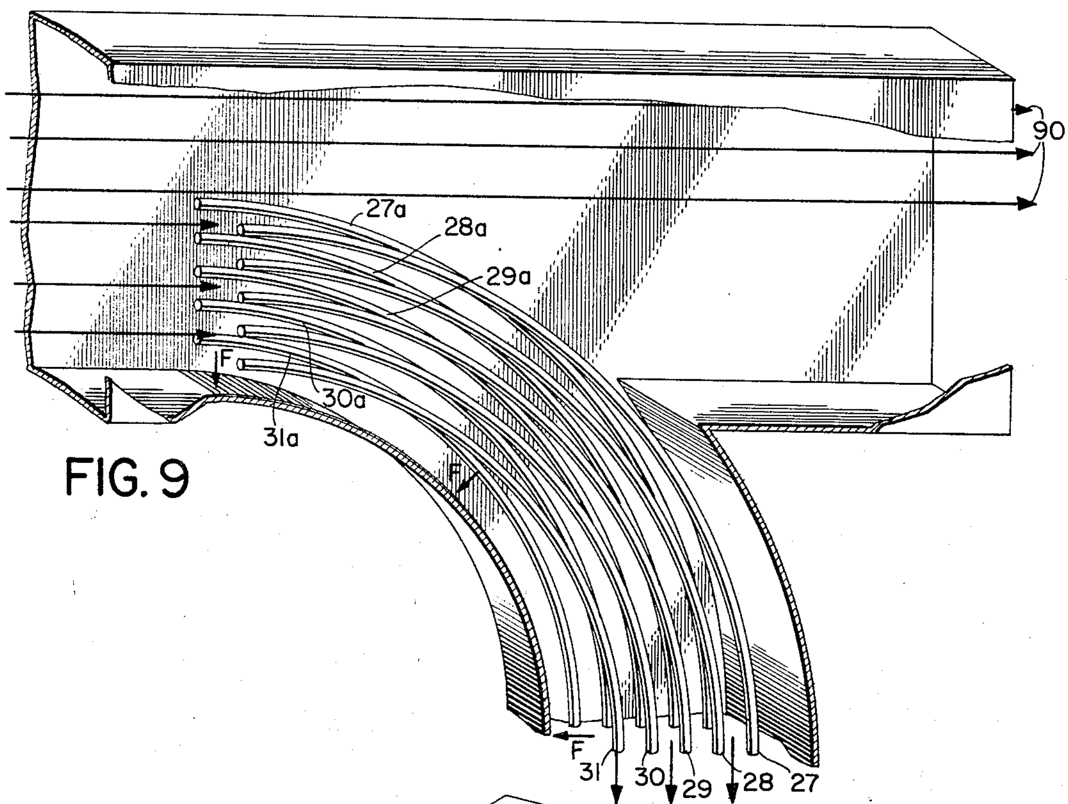

FIG. 9

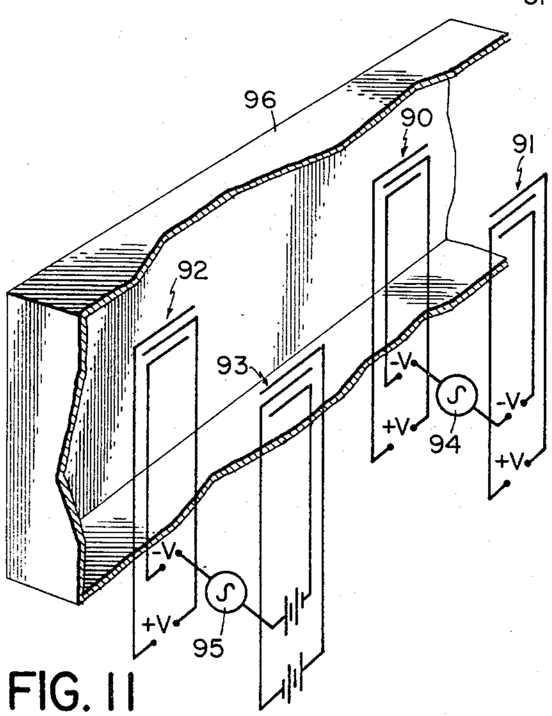

FIG. 11

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3,407,323
ELECTRODE STRUCTURE FOR A CHARGED PARTICLE ACCELERATING APPARATUS, ARRAYED AND BIASED TO PRODUCE AN ELECTRIC FIELD BETWEEN AND PARALLEL TO THE ELECTRODES

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11 Claims. (Cl. 313—63)

ABSTRACT OF THE DISCLOSURE

An apparatus for moving a charged particle beam which consists of a pair of electrodes, having a controlled resistance drop in one direction, which have been biased to produce equipotential lines between the electrodes such that the resultant electric field between the electrodes is parallel to the electrodes.

This invention relates generally to the manipulation of charged particle beams and more particularly to a novel electrode structure for manipulation of charged particle beams by electric fields.

Both magnetic and electrostatic systems have been used to manipulate charged particle beams. In most applications electrostatic systems are preferred over magnetic systems for they are linear and do not exhibit hysteresis or residual fields. All prior art electrostatic beam handling systems basically comprise a pair of opposed electrodes with potentials applied between them to produce an electric field normal to the electrode surface. Such systems are exemplified by the electrostatic deflection plates found in cathode ray tubes.

Although this system is widely known and used it has an inherent limitation in that a minimum width to gap ratio must be maintained to provide uniform fields between the electrodes. Therefore, to achieve meaningful electrode gaps the opposing electrode areas must be relatively large. With increasing electrode area the probability of electric breakdown of the applied electric field, across the single gap, increases proportionately with the electrode area.

Furthermore, with increasing electrode area it becomes more difficult to condition such systems to hold maximum potentials. An increase in the power required to maintain the desired potential across the gap occurs because currents exist across the single gap even when a charged particle beam is not passing through the gap. Moreover, when a beam is introduced into the gap, breakdown occurs more readily due to cumulative ionization because both random charged particles and their generated secondaries are subjected to the total gap potential.

These drawbacks are particularly noted and become quite troublesome in systems which are required to manipulate beams whose particle energy is in the mev. range or higher.

The present invention was designed to avoid and to overcome all the drawbacks and disadvantages encountered in the prior art electrostatic deflection systems. The present invention thus provides an electrostatic deflection system in which the field uniformity, in the central region, is not a function of the width to gap ratio thereby reducing the breakdown probability and lowering the required power. Additionally the present invention minimizes the possibility of unwanted particles being swept out of the system from impacting the electrodes and causing field perturbations and eliminating cumulative ionization to reduce the loading of the system.

Moreover, the invention may be used as a beam scoop

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to extract a portion of a beam from a chamber without disturbing the remainder of the beam.

Broadly speaking, these and other advantages and features of the present invention are obtained by biasing a pair of opposing electrodes to produce equipotential lines between the electrodes such that the resultant electric field between the electrodes is parallel to the electrodes.

The present invention and various modifications and embodiments thereof will be best understood by perusal of the following specification taken in conjunction with the attached figures wherein:

FIG. 1 illustrates the field and equipotential lines of the prior art.

FIG. 2 illustrates one embodiment of the invention.

FIG. 3 an end view of the embodiment of FIG. 1 shows the power supply circuit and field and equipotential lines.

FIG. 4 shows a different embodiment of the invention.

FIG. 5 shows a modified electrode array.

FIG. 6 illustrates the invention used as a storage ring.

FIG. 7 shows the apparatus of FIG. 6 modified by the incorporation of a dumping section.

FIG. 8 illustrates the invention used as an electrostatic orbital accelerator.

FIG. 9 shows the apparatus of FIG. 4 used as a beam scoop.

FIG. 10 shows still another embodiment of the electrode array.

FIG. 11 illustrates the invention used as an RF beam separator, and

FIG. 12 illustrates another embodiment of the invention using resistive materials as the electrodes.

Considering first the prior art there is shown in FIG. 1 the simple case of a pair of flat parallel metal plates **10** and **11** that are oppositely charged by a battery **12**. Immediately upon the charging of the plates, field lines, shown as solid arrows **13**, are produced and extend across the gap **14** from plate **10**, positively charged, to plate **11**, negatively charged. Simultaneously, equipotential lines, shown by dashed lines **15**, are created parallel to the plates and perpendicular to the field lines. Because the plates are not infinite in length the field and equipotential lines become distorted at the plate edges.

If a beam of charged particles, for example electrons or ions, are permitted to pass between these plates under the above conditions, the charged particle means will be deflected along the field lines towards the oppositely charged plate. If the applied plate polarity is reversed, the deflection will also be reversed. In such a device particles of different velocities traverse the field in different times and consequently are deflected by correspondingly different amounts.

Turning now to FIGS. 2 and 3 the basic principles of the invention will be described. In these views the invention has been reduced to its simplest components and is shown as a first elctrode array **21** and a second electrode array **22** contained within a hollow evacuated chamber **20** which contains an opening **26** through which charged atomic or nuclear particles may pass. Each array comprises a multiplicity of rod electrodes held in a rigid stacked arrangement by a plurality of insulating standoff spacers **32** which serve to isolate the electrodes from each other and from the walls of chamber **20** which is at ground potential **25**. In this view the electrodes comprising array **21** are numbered **27**, **28**, **29**, **30** and **31**. While the electrodes comprising array **22** are numbered **27***a*, **28***a*, **30***a* and **31***a*. Although five electrodes are shown in each array it should be understood that this number can be increased or decreased or greatly modified, as will be discussed later, and still remain within the scope of the present invention.

Each electrode is electrically connected through resistors to a suitable power supply shown as batteries 23 and 24 to impose a voltage gradient between each electrode in the array. The central electrode in each array is grounded and is coupled to each adjacent electrode by a dropping resistor which in turn is coupled to its adjacent electrode by a resistor, with the outer most electrodes being connected directlly to the power supplies.

Thus, for example, in array 21 electrode 29 is grounded and connected to electrodes 28 and 30 by means of dropping resistor 33 and 34 respectively. Electrode 28 is, in turn, coupled to its adjacent electrode 27 through a resistor 35. Electrode 27 being the end electrode is coupled directly to the positive side of supply 23 whose negative side is tied to ground 25. Electrode 30 is coupled via resistor 36 to electrode 31 which is directly connected to the negative side of supply 24 whose positive side is tied to ground 25. Array 22 is coupled in a similar manner to the same power supplies as shown in FIG. 2.

This creates electrical pairing of the two arrays and creation of electric field lines 36 between and parallel to the arrays. Thus the field lines 36 are lateral to or parallel to the arrays. Since each electrode in an array is electrically paired with its counter-part in the other array, that is electrode 27 is paired with electrode 27*a*, 28 with 28*a*, 29 with 29*a*, 30 with 30*a* and 31 with 31*a*, equipotential lines 27*b* through 31*b* are established between each electrode pair.

A stream of charged particles passing between the arrays becomes deflected along the field lines. However, in this case the field lines are parallel to the array of electrodes and not perpendicular thereto.

With this electrode construction, the field uniformity in the central region becomes a function of the distance of the central region from the local field distortion near the individual electrodes. The total applied potential is divided uniformly across the gaps between the electrodes, thus reducing the effect of electrode area. Because the total applied voltage is broken into discrete steps the probability of breakdown between the electrodes is small. This will perhaps be better understood from the following brief discussion regarding ionization in the system.

In the first case we will assume that, as shown in FIG. 3, a positively charged ion 37 exists either at the surface of electrode 27 or in the gap between the electrodes 27 and 28. The applied electrostatic forces will urge this ion along the field lines toward the negatively charged electrode 30. However, it will be difficult if not impossible for this ion, because of the field geometry, to travel to any other electrode except electrode 28. In traversing the gap between electrodes 27 and 28 the total energy gained by the ion would be $2eV/n$ where e is the electronic charge of the ion, V is the voltage applied and n is the number of gaps in the system. The probability of this ion traversing the entire potential $2e$V, that is, traveling directly from electrode 27 to electrode 31 is negligible since the field lines between the electrodes assume the shortest possible length and thus will terminate in the next adjacent electrode. Additionally the cumulative effects of ionization are also less since any secondary ions, that are created, would experience the same difficulty in gaining the total energy $2e$V. In the prior art system an ion 38 on the surface of one electrode would upon striking the opposite electrode have a total energy of $2e$V whereupon a loading of the electrode and secondary emission would occur.

In the other case we will assume that an ion 39 exists in the central region away from the electrodes on one of the equipotential lines. Considering only the worst case, which is where a positive ion 39 is on the equipotential line 27*b* we find the ion can travel to the nearest wall 40 of chamber 20 arriving with an energy eV, or it can traverse the field striking the electrode 31, with an energy $2e$V or continue and strike the opposite wall 41 of chamber 10 with an energy eV.

Because the area of electrode 31 is small and the probability of an ion striking it is also small and the most likely case is that these ions will strike the chamber wall 41 within energy eV. The energy of particle 39 when traveling along the field lines toward wall 41 will increase as it crosses each equipotential line until it reaches a maximum energy $2e$V upon crossing line 31*b*. After crossing line 31*b* it is decelerated to an energy eV with which it strikes wall 41. Thus the possibility of generating secondary emission from the wall is less than that of the prior art.

The other possibility of generating secondary electrons occurs if the ion strikes a gas molecule. Since chamber 20 will, in usage, be highly evacuated this probability is also small.

The above described probabilities and possibilities also holds true of secondary particles. Since all the ionization currents are reduced the power required by this system is reduced proportionally.

In the case where a beam is injected between the electrode array along the centerline 43 conditions are also improved.

When an injected beam having a wide energy spectrum, is introduced into the chamber along centerline 43, the diverted particles of unwanted energy travel along the field direction to strike the chamber walls and not the electrodes thus eliminating heating of and cumulative ionization on the electrodes. Furthermore because the injected beam is in the center of the system, which is substantially at ground potential, any ions created by the beam striking gas molecules strike the chamber walls at low energy thus reducing the probability of secondary emission. The elimination of cumulative ionization on the electrode reduces the loading on the system. Furthermore because the chamber walls now act as the collector for unwanted ions the cooling problem is significantly reduced and the need of elaborate, insulated, electrode cooling systems is eliminated. All that is now required is that cooling be applied directly to the chamber walls which are at ground potential.

Numerous modifications or embodiments, of the present invention, may now become obvious. For example, by constructing all portions of the device from non magnetic material and placing magnet poles 110 and 111 across the electrode array a crossed magnetic field effect may be added to the electric field whereby increased deflection power is obtained.

The present invention may also be used to deflect charged particle beams in a circular or semi circular path. FIG. 4 shows an apparatus, utilizing the present invention, designed to turn the beam 90°. In this view a pair of electrode arrays 41 and 42, each consisting of a plurality of equispaced electrodes 51, 51*a*, 52, 52*a*, 53, 53*a*, 54, 54*a*, 55, 55*a*, 56 and 56*a* are formed to describe the quadrant of a circle. These arrays are biased in a similar manner as shown in FIG. 3. This biasing arrangement creates an electric field which is directed towards the center of circle as shown by field lines 43. This field arrangement causes a beam entering one end of the structure along a line 45 to be deflected such that it emerges from the structure along a line 46 which is at right angles to line 45. When the particles comprising the beam have different energies they are all deflected different amounts. In this case the main portion of the beam will pass out of the structure along line 46, but those portions, which are of greater energy will pass out of the structure along tangents 47 and 48 and those of lesser energy will travel in tighter circular paths 49 or 50.

By providing openings in the chamber wall different mass particles can be extracted from the chamber without causing perturbations in the created electric field.

If it is desired that the entire beam entering along line 45 be emitted along line 46, even though all particles are not exactly at the same energy, the electrode structure may be modified such that this rejection of different particles is minimized.

This modified electrode structure is shown in FIG. 5, where for the sake of simplicity and clearness the numerical designations used in FIG. 4 will be used again. In this modified structure the electrodes become more closely packed as their radius increases. Thus for example, electrodes **51** and **52** are closer together than are electrodes **55** and **56**. Additionally, the bias applied to each electrode is varied. For example, electrode **56** could be at ground potential, electrode **55** at some potential V, electrode **54** at a potential 2V and ΔV, electrode **53** at a potential $3V+2\Delta V$, electrode **52** at a potential $4\Delta+3\Delta V$ and electrode **51** at a potential $5V+4\Delta V$. This electrode and biasing arrangement creates an electric field which increases in strength proportional to the increase in potential and electrode packing density.

Thus, in this structure, a beam passed into it along the line **45** will be emitted along the line **46**. The entire beam is confined between the electrodes and will pass out of the array along the line **46** because particles with higher energies etc. will tend to go towards the outside of the array e.g. towards electrodes **51, 51*a*** where they encounter a stronger field which deflects them more strongly while particles with lower energies go towards the inner electrodes **56, 56*a*** where the weaker field deflects them less strongly.

By taking advantage of this flexibility and by forming the electrodes such that they assume a ring shape the invention may be utilized as a particle or beam storage ring. This is shown in FIG. 6. For the sake of simplicity only electrodes **56, 56*a*** and **51, 51*a*** are shown. The packing and biasing arrangement can be the same as shown in FIG. 5. In this device the particles introduced into the space between the electrode arrays would remain therein on particular radial paths until released. If the particles are non-relativistic in energy then the required field strength and thence the potentials required on each electrode may be readily determined from the equation

$$eE=mv^2/R$$

where E is the field, e the electronic charge, m the particle mass, v the particle velocity and R the radius of the desired orbit.

Radial focusing is accomplished by arranging increasing electric field outside the desired radius and decreasing field inside the desired radius. In this way the particles will be confined to a particular orbit for when they begin to stray they will be returned by the field configuration. To remove the particle from the ring the field must be extinguished and the particles will leave on a path tangential to radial path they were following at that time.

The above described storage ring can be modified such that it will eject the stored particles along a particular path or at a desired time. This is accomplished by providing in the ring a beam dumping section such as is shown in FIG. 7.

In this device a segment of each ring is isolated from the remainder of the ring. These segments are shown as **51*c*, 56*c*, 51*d*** which are seperated from their respective rings **51, 56, 51*a*** and **56*a*** by insulating gaps **71** and **72**. This sectionalized portion **70** is separately biased in the same manner as the rest of the device. When it is desired to eject the contained particles, the potentials on this section **70** are decreased rapidly such as by shorting to ground and the particle beam will emerge from the storage ring tangentially to the shorted out section.

This invention may also be used as an electrostatic orbital accelerator. This embodiment is shown in FIG. 8. In this view the apparatus is shown schematically, and comprises four semicircular electrode arrays **80, 81, 82** and **83** separated by gaps **85** and **86**. Each array consists of a plurality of electrodes either as discussed in FIG. 5 or FIG. 1. In the preferred embodiment the electrode arrangement of FIGS. 2 and 3 would be used. That is, each electrode would be equally spaced from each other electrode. For purposes of illustration only three electrodes are shown in each array, a positive, a negative and a ground. Each electrode would be separately biased such that a radial field is established between the arrays. This radial field will keep an injected particle in a predetermined orbital path. The biasing shown in FIG. 8 is for positively charged particles. That is the outermost electrodes in each array is positive and the innermost electrode at a negative potential with the ground electrode centrally located in the array.

Once the particle is injected in the field it follows a semicircular path of radius proportional to its velocity and orbits around the ring from segment to segment. (Thus the invention is a modified cyclotron in which an electrostatic field is substituted for the magnetic field.) By superimposing an alternating electric field on the D.C. bias applied to the electrodes and across the gaps **85** and **86** and this oscillation adjusted such that the particle enters the gaps **85** and **86** to be pulled by the A.C. field, in the direction that it is already traveling and increase its speed at each crossing of the gaps.

The invention may also be used as a beam scoop as shown in FIG. 9. In this embodiment the electrode arrays are curved as illustrated in FIG. 4 and have the same potentials applied thereto. By positioning this structure such that it intercepts only a portion of a broad beam that portion so intercepted may be extracted while leaving undisturbed the remainder of the beam. Such partial extraction is used for measurement purposes. This configuration may also be used to extract lower energy particles from a highly energetic beam.

Turning now to FIG. 10 there is shown in schematic cross section an embodiment of the present invention designed to produce high, intense fields while providing long surface insulation paths. In this view, the outer electrodes **180, 181, 183, 184** and **180*a*, 181*a*, 183*a*, 184*a*** are each formed in a dog-leg manner such that in the central portion of the array they become closely packed towards the grounded control electrode **182** while at the outer ends they are widely separated and insulated from one another by long bar like insulators **85**. Such an embodiment is to be preferred in many applications since the long surface insulation paths are obtained. If desired the surfaces of the insulators **85** could be corrugated to provide even longer paths.

FIG. 11 shows the invention used as a radio frequency beam velocity separator. Such separators depend on the mass-dependent velocity difference among particles in a beam of well defined momentum. In this application four arrays **90, 91, 92** and **93** are used with array **90** being paired with array **91** and array **92** paired with array **93**. Each array would have potentials applied thereto as illustrated and described in FIGS. 2 or 3. Additionally an R-F signal would be superimposed on each array pair from a suitable generator **94** and **95**.

Each R-F separator will be contained in a single chamber **96** but separated from each other by a suitable drift space. Thus transmit time of the particles through the pair of arrays and drift space determines the relative phase of the particle deflection. With this system the resultant deflection of one particle can be made greater than the deflection of a different particle while leaving a third particle undisturbed. The amplitude and phase of the deflecting R-F fields must be held constant with respect to one another.

Still further this present invention may be modified by changing the shape of the ends of each electrode array so as to cause the fringing electric fields to be more uniform. Additionally if it is desired to define the entrance and exit fields accurately for optical reasons, grid wires may be connected between the electrodes which have the highest potential applied thereto.

Having now described several embodiments and applications of the present invention and because other adaptations may now become apparent to those skilled in the art, for example the electrode array of individual electrodes could be replaced by known resistive materials such as semiconductors to provide selected voltage drops without requiring coupling resistors, such an adaptation is shown in FIGURE 12 where parallel plates **101** and **102** of controlled resistive material such as sheets of semiconductive material are used as the electrodes. For clarity the surrounding chamber has been omitted from this figure.

To achieve the effects of the present invention these plates **101** and **102** must be biased as shown in FIGURE 12, that is to say, one end of a plate must be biased positive, for example, end **103** of plate **101**, and its opposite end **105** biased negatively. The other plate **102** must be correspondingly biased so that end **104** is biased positively and end **106** biased negatively. This arrangement creates an electric field in a direction, shown by the arrow **107**, which is parallel to and between the electrodes **101** and **102**. Such electrodes can be used in lieu of the arrays of, for example, FIGURES 2 or 6. Thus it is desired that the present invention be limited only by the following claims.

What is claimed is:

1. A charged particle beam manipulation apparatus comprising an evacuated chamber, said chamber being at ground potential only a single pair of electrode means insulatively maintained in said chamber in plane parallel opposition, means for directing a charged particle beam through said chamber and between said electrode means, each of said electrode means having a controlled resistance drop in at least one direction, and power supply means for applying an electric potential to each of said electrode means to establish a controlled voltage drop across each of said electrode means in the direction of said controlled resistance to establish an electric field between said electrode means and parallel to the plane of said electrode means, said electric field being in the direction of said controlled voltage drop, said electrode means comprising an array of conductive rods, each rod being resistively coupled to the next adjacent rod and insulated from said chamber walls.

2. The apparatus of claim **1** wherein each of said rods are arcuate to form an electrode which describes the quadrant of a circle.

3. The apparatus of claim **1** wherein the conductive rods comprising said arrays are equally spaced from one another.

4. The apparatus of claim **1** wherein said rods are more densely packed in one direction across said array and said applied potential increases in value in proportion to said increase in rod density.

5. The apparatus of claim **1** wherein said rods are more densely packed in one direction across said array.

6. A charged particle beam manipulation apparatus comprising an evacuated chamber, said chamber being at ground potential, only a single pair of electrode means insulatively maintained in said chamber in plane parallel opposition, means for directing a charged particle beam through said chamber and between said electrode means, each of said electrode means having a controlled resistance drop in at least one direction, and power supply means for applying an electric potential to each of said electrode means to establish a controlled voltage drop across each of said electrode means in the direction of said controlled resistance to establish an electric field between said electrode means and parallel to the plane of said electrode means, said electric field being in the direction of said controlled voltage drop, each of said electrode means being composed of an array of concentric rings, the innermost of said rings having the lowest potential applied thereto and the outermost ring having the highest potential applied thereto, said applied potentials creating a radially inwardly directed electric field parallel to the plane of said arrays.

7. The apparatus of claim **1** wherein said electrode means and said chamber define an arc and a multiplicity of beam exit ports in said chamber.

8. A charged particle beam manipulation apparatus comprising an electrically grounded, evacuated chamber, only a single pair of electrode means enclosed in said chamber, said electrode means insulatively maintained in said chamber in plane parallel opposition, means for directing a charged particle beam through said chamber and between said electrode means and means for creating a charged particle deflection force between said electrode means and parallel thereto, each of said electrode means being composed of a plurality of concentric rings, said creating means comprising D.C. power supplies coupled to said electrode means to create a radial inwardly directed electric field between and parallel to the electrode means, and each of said electrode means being provided with a segment electrically separable from the remainder thereof, said segments being provided with means for reducing the field between said segments to zero.

9. A charged particle beam manipulation apparatus comprising an electrically grounded, evacuated chamber, only a single pair of electrode means enclosed in said chamber, said electrode means insulatively maintained in said chamber in plane parallel opposition, means for directing a charged particle beam through said chamber and between said electrode means and means for creating a charged particle deflection force between said electrode means and parallel thereto, each of said electrode means comprising a flat circular ring having a controlled resistivity in a radial direction.

10. A charged particle beam manipulation apparatus comprising an electrically grounded, evacuated chamber, only a single pair of electrode means enclosed in said chamber in plane parallel opposition, means for directing a charged particle beam through said chamber and between said electrode means and means for creating a charged particle deflection force between said electrode means and parallel thereto, each of said electrode means having a first segment and a second segment, electrical isolation means separating each segment from the other segment, said creating means comprise D.C. power supplies coupled to said electrode means to create a radial electric field in the plane of said electrodes and an A.C. signal source coupled across said electrical isolation means to accelerate charged particles traveling in a circular path between said electrode means and traversing said isolation means.

11. A charged particle accelerator comprising an evacuated hollow chamber enclosing therein a closed orbital path along which charged particles may travel, means for injecting charged particles into said chamber, means in said chamber for producing radial electric fields to confine the injected particles to orbital paths, said field producing means comprising two arrays of arcuate electrodes electrically insulated from each other and from the chamber, means for applying a D.C. potential to each of said arrays to create a radially, inwardly directed, electric field, and means for applying to each electrode array a high frequency signal, said signal being synchronized to the velocity of said particle to apply an accelerating electric field to the particle as it travels from one array electrode to the other.

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