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(54) PARTICLE ACCELERATOR AND METHOD OF REDUCING BEAM DIVERGENCE IN THE PARTICLE ACCELERATOR

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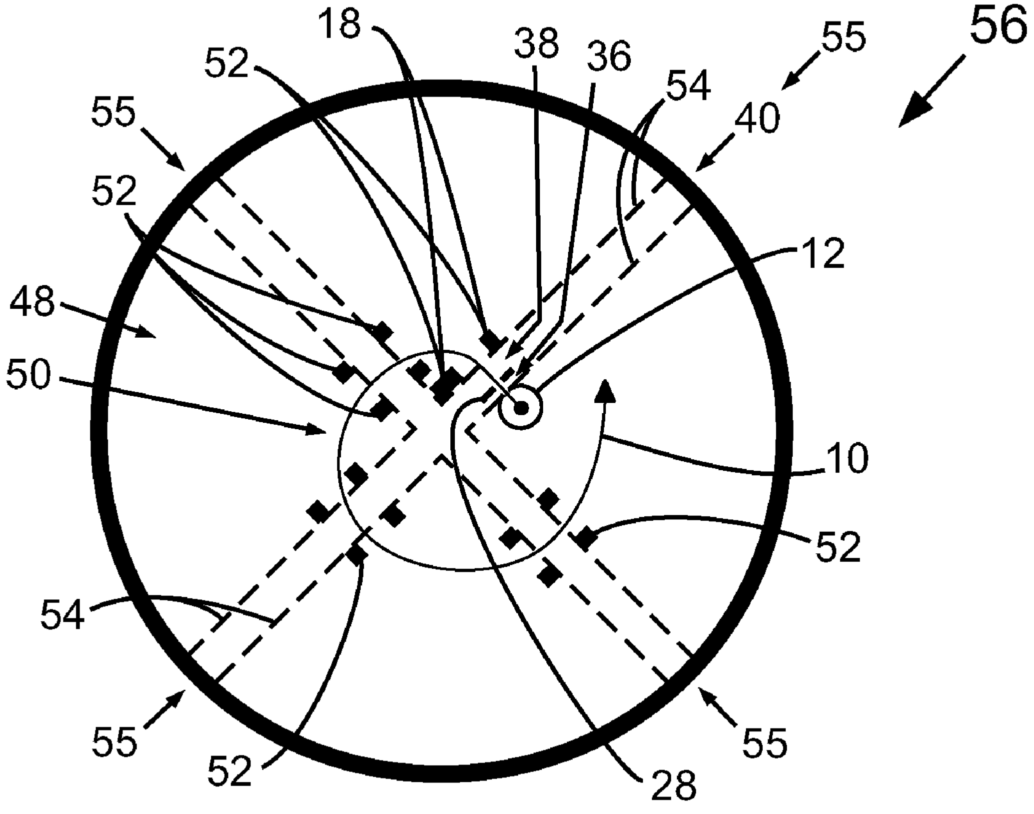
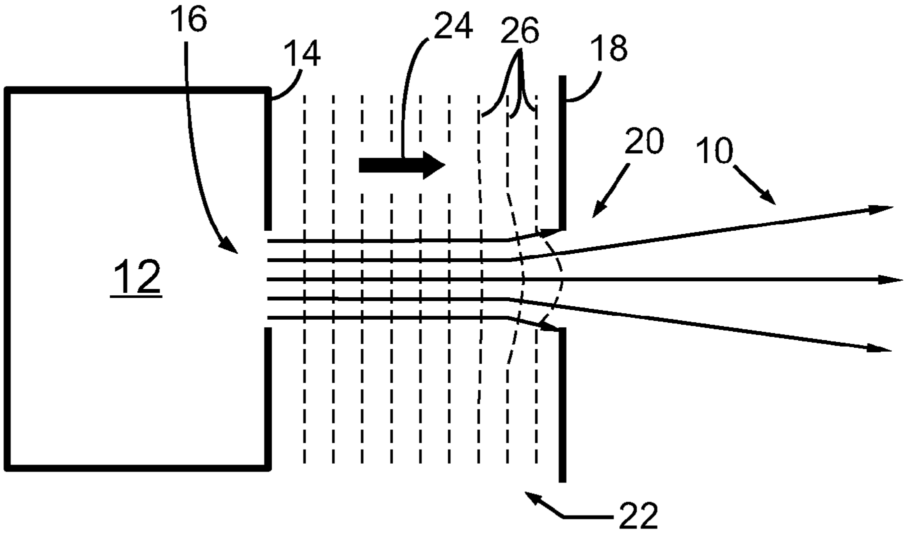
(57) ABSTRACT

An oscillating field particle accelerator and a method of reducing beam divergence in the particle accelerator are provided. The particle accelerator includes an intermediate electrode disposed within the particle accelerator between a source of charged particles and a second electrode of the particle accelerator. The charged particles are exposed to a first electric field extending between the source and the intermediate electrode prior to being exposed to a second electric field extending between the intermediate electrode and the second electrode. The magnitude of the first electric field is less than the peak magnitude of the second electric field, and may be less than or equal to a minimum magnitude of the second electric field occurring during a phase acceptance time period associated with a phase acceptance of the particle accelerator. The accelerated charged particles emerge from the second electrode as a non-diverging or reduced divergence particle beam.





---- PRIOR ART ----

FIG. 1A

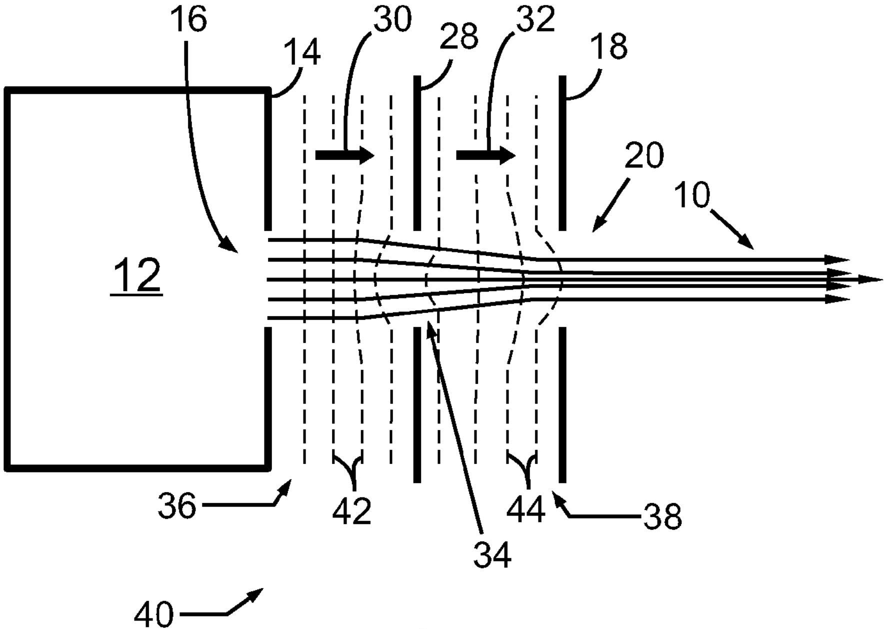


FIG. 1B

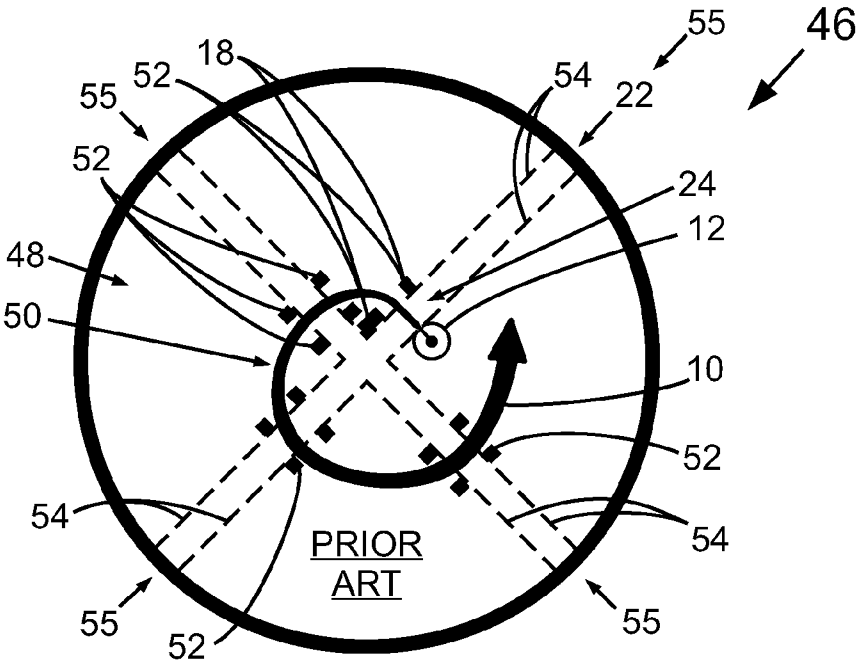

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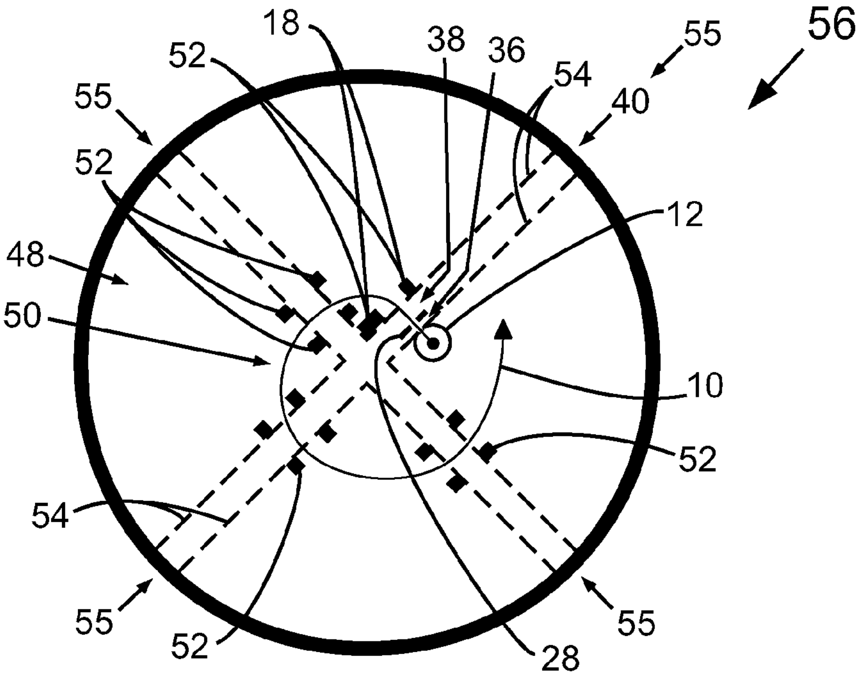
FIG. 2A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18
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40
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12
48
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10
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52
55
28

FIG. 2B

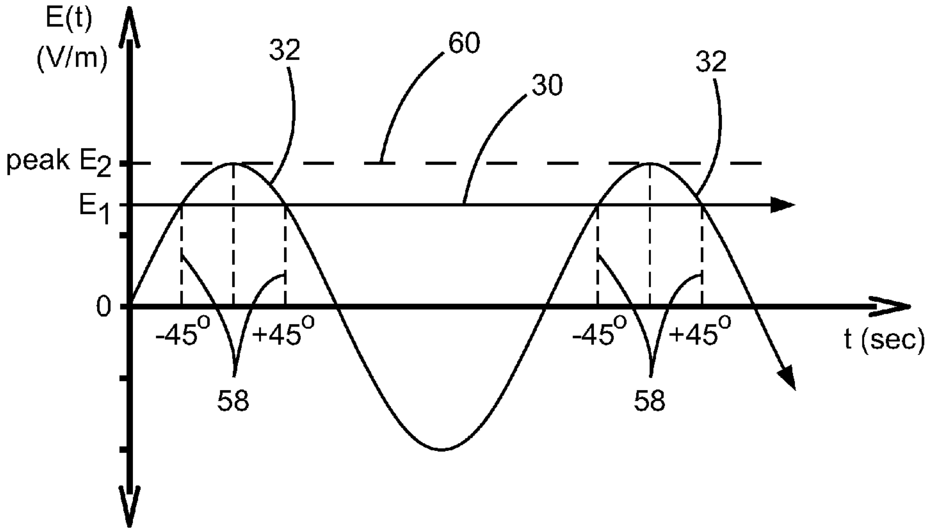

E(t)
(V/m)
32
60
30
32
peak E_2
E_1
0
-45°
+45°
58
-45°
+45°
58
t (sec)

FIG. 3

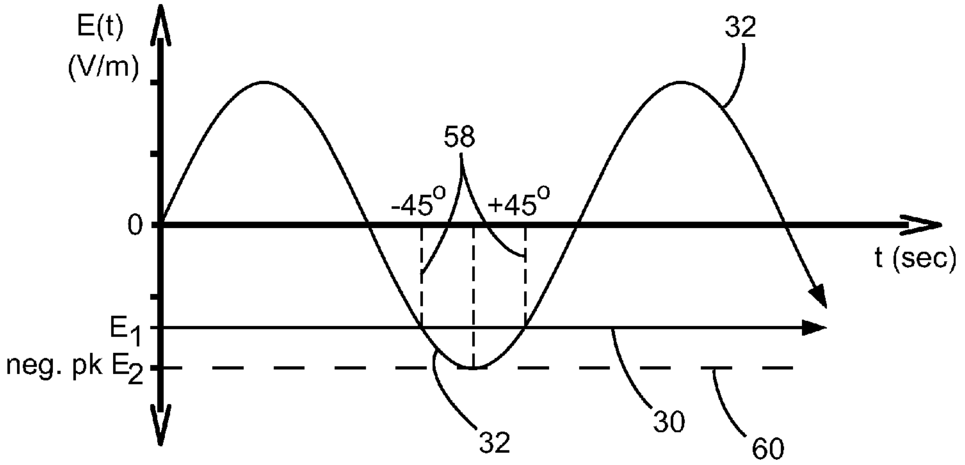
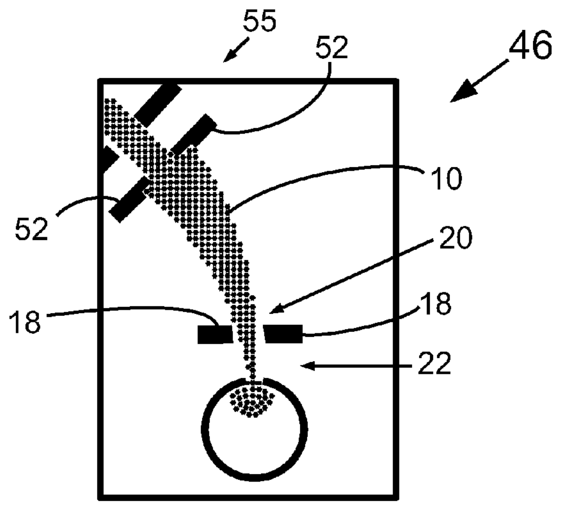

E(t)
(V/m)
32
58
-45°
+45°
0
t (sec)
E_1
neg. pk E_2
32
30
60

FIG. 4



---- PRIOR ART ----

FIG. 5A

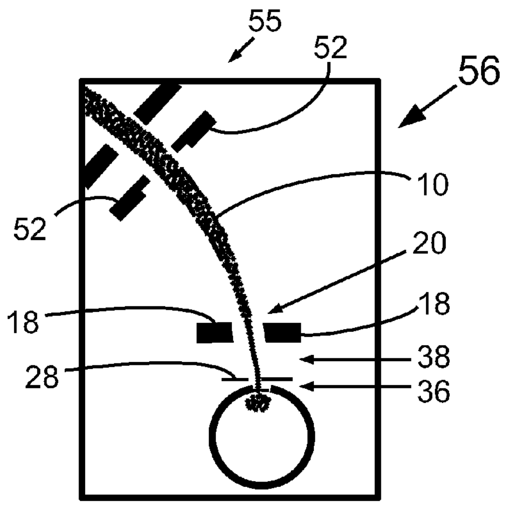


FIG. 5B

PARTICLE ACCELERATOR AND METHOD OF REDUCING BEAM DIVERGENCE IN THE PARTICLE ACCELERATOR

FIELD OF THE INVENTION

[0001] This invention relates to beam dynamics in oscillating field particle accelerators and, in particular, to a method of reducing beam divergence in a particle accelerator, the use of an intermediate electrode for reducing beam divergence in a particle accelerator, and particle accelerators having such intermediate electrode.

DESCRIPTION OF RELATED ART

[0002] Oscillating field particle accelerators use electric fields, which are typically made to oscillate at radio frequencies (e.g. from 10 MHz to 3 GHz), to produce an accelerated beam of charged particles after such particles are received from ion sources. Ion sources are sources of electrically charged particles.

[0003] Circular particle accelerators, such as cyclotrons, synchrocyclotrons, isochronous cyclotrons, FFAG accelerators, betatrons and synchrotrons, bend the particle beam. For example, circular particle accelerators can use magnetic fields to bend the electrically charged particles along a circular path. Linear accelerators (LINACs) accelerate the beam particles along a straight path inside a straight, elongated chamber.

[0004] In a conventional oscillating field particle accelerator with an internal ion source, a beam of charged particles is extracted from the internal ion source via an electric field generated in an acceleration gap defined between an output aperture of the ion source and an electrode, which may be a radio frequency resonator electrode. The electrode includes an aperture from which the particle beam emerges into the main body of the particle accelerator. Initial acceleration of the particle beam occurs in the acceleration gap as a result of a non-zero electric field within the acceleration gap, whereas further beam guidance and acceleration occurring in the main body of the particle accelerator typically involves both electric and magnetic fields and is independent of any interaction with the ion source itself.

[0005] However, the particle beam emerging from the electrode through the aperture into the main body of the conventional particle accelerator with an internal ion source is a diverging beam. The fact that the emerging beam is divergent causes beam losses and necessitates beam focusing in the main body of the particle accelerator.

[0006] U.S. Pat. No. 3,867,705 to Hudson et al. discloses a slotted dc accelerating electrode positioned between an existing ion source arc chamber and an existing rf accelerating slit, and a source of substantially large negative voltage connected to the dc accelerating electrode, whereby, during operation of the cyclotron, heavy ion beams being accelerated in the cyclotron on harmonics from the 5th to the 11 th harmonic have their beam intensities increased from nanoamperes to microamperes by use of the dc accelerating electrode in the cyclotron. However, the substantially large negative voltage connected to the dc accelerating electrode, while increasing beam intensities for the 5th to 11 th harmonic of the beam, causes a reduction in focusing and/or increased defocusing of the beam.

[0007] In a conventional oscillating field particle accelerator with an external ion source, the external ion source is a stand-alone beam extraction system which may include double-gap acceleration in an 'accel-accel' configuration such that the particle beam at the output of the stand-alone beam extraction system is non-diverging. However, the particle beam produced by the external ion source is a low-energy beam requiring further initial acceleration. The external ion source is connected to the conventional oscillating field particle accelerator such that the particle accelerator receives the particle beam from the external ion source into an acceleration gap of the particle accelerator. The acceleration gap, which is internal to the particle accelerator, has therewithin a non-zero electric field produced by an electrode, which may be a radio frequency resonator electrode. The beam particles are accelerated through the electric field acceleration gap and emerge into the remainder (e.g. main body) of the particle accelerator via an aperture of the electrode.

[0008] However, the particle beam emerging from the electrode through its aperture is a diverging beam in a conventional oscillating field particle accelerator with an external ion source.

[0009] In a conventional linear accelerator, beam particles are accelerated within an acceleration gap formed between cylindrical or tube-like electrodes which are spaced apart and longitudinally aligned. Every second cylindrical electrode is at ground potential, and a non-zero voltage is applied to every second other electrode interleaved between the ground potential electrodes. The applied voltage produces an electric field in each gap between adjacent cylindrical electrodes, while an electric field is not produced within the cylindrical electrodes themselves. By varying the voltage applied to every second other electrode with appropriate timing, charged particles experience a cascade of accelerating forces when passing through each acceleration gap and "coast" through the cylindrical electrodes. It is known that such configuration of acceleration gaps causes a weak focusing of the linearly accelerated particle beam.

[0010] However, the weak focusing of the linear acceleration configuration is insufficient to avoid divergence of particle beams within a linear accelerator.

[0011] In a conventional oscillating field particle accelerator, a sinusoidal electrical voltage is applied to the radio frequency resonator electrode. Charged particles being accelerated by the particle accelerator are accepted into the main body of the particle accelerator from an initial acceleration region of the particle accelerator within a range of voltages and corresponding phases about a peak of each 360 degree cycle of the sinusoidal voltage. Within a corresponding range of voltages and associated phases about the opposite polarity peak of each cycle of the sinusoidal voltage, acceleration of the charged particles is reversed and the charged particles are prevented from entering the main body of the particle accelerator. In the case of accelerating positively charged particles or ions, the maximum beam current of the beam entering the main body occurs at or near the negative peak of each cycle of the sinusoidal voltage. Conversely, the maximum beam entry current of a beam of negatively charged particles or ions occurs at or near the positive peak of each cycle of the sinusoidal voltage. Phase acceptance is defined as the phase range within each cycle of the sinusoidal voltage during which the charged particles are accepted into the main body of the particle accelerator. The phase acceptance time period is the time period of each cycle of the sinusoidal voltage during which the charged particles are being accepted into the main body of the particle accelerator.

[0012] An object of the invention is to address the above shortcomings.

SUMMARY

[0013] The above shortcomings may be addressed by providing, in accordance with one aspect of the invention an oscillating field particle accelerator for accelerating charged particles. The particle accelerator includes an intermediate electrode disposed within the particle accelerator between a source of the charged particles and a second electrode of the particle accelerator, the charged particles being exposed to a first electric field extending between the source and the intermediate electrode prior to being exposed to a second electric field extending between the intermediate electrode and the second electrode, the magnitude of the first electric field being less than a peak magnitude of the second electric field.

[0014] The second electrode may have a time-varying voltage applied thereto such that the second electric field is time-varying. The time-varying voltage may be sinusoidal. The intermediate electrode may have a DC voltage applied thereto such that the magnitude of the first electric field is substantially non-varying in time. The intermediate electrode may be disposed closer to the source than the intermediate electrode is to the second electrode. The intermediate electrode may define an intermediate aperture for permitting the charged particles to pass through the intermediate electrode, the intermediate aperture having an oblong shape. The particle accelerator may be a circular type oscillating field particle accelerator. The particle accelerator may be a cyclotron. The second electrode may be an extraction electrode. The source may be internal to the particle accelerator. The magnitude of the first electric field may be less than or equal to a minimum magnitude of the second electric field occurring during a phase acceptance time period associated with a phase acceptance of the particle accelerator. The phase acceptance may be in a range of 0 to 90 degrees. The phase acceptance may be in a range of 20 to 50 degrees. The intermediate electrode may have a voltage applied thereto such that the waveform of the magnitude of the second electric field during the phase acceptance time period and the waveform of the magnitude of the first electric field during a corresponding time period offset from the phase acceptance time period have substantially equal waveform shapes.

[0015] In accordance with another aspect of the invention, there is provided a method of reducing divergence of a beam of charged particles in an oscillating field particle accelerator. The method involves passing the charged particles through a first electric field from a source of the charged particles toward an intermediate electrode disposed within the particle accelerator and then passing the charged particles through a second electric field from the intermediate electrode toward a second electrode of the particle accelerator when the magnitude of the first electric field is less than a peak magnitude of the second electric field.

[0016] The charged particles may be passed through the second electric field when a time-varying voltage is being applied to the second electrode such that the second electric field is time-varying. The charged particles may be passed when the time-varying voltage is sinusoidal. The charged particles may be passed through the first electric field and then through the second electric field when the intermediate electrode has a DC voltage applied thereto such that the magnitude of the first electric field is substantially non-varying in time. The charged particles may be passed through the first electric field and then through the second electric field when the intermediate electrode is disposed closer to the source than the intermediate electrode is to the second electrode. The charged particles may be passed through the first electric field and then through the second electric field when the intermediate electrode defines an intermediate aperture for permitting the charged particles to pass through the intermediate electrode and the intermediate aperture has an oblong shape. The charged particles may be passed through the first electric field and then through the second electric field when the particle accelerator is a circular type oscillating field particle accelerator. The charged particles may be passed through the first electric field and then through the second electric field when the particle accelerator is a cyclotron. The charged particles may be passed through the first electric field and then through the second electric field when the second electrode is an extraction electrode. The charged particles may be passed through the first electric field and then through the second electric field when the source is internal to the particle accelerator. The charged particles may be passed through the first electric field and then through the second electric field when the magnitude of the first electric field is less than or equal to a minimum magnitude of the second electric field occurring during a phase acceptance time period associated with a phase acceptance of the particle accelerator. The charged particles may be passed through the first electric field and then through the second electric field when the phase acceptance is in a range of 0 to 90 degrees. The charged particles may be passed through the first electric field and then through the second electric field when the phase acceptance is in a range of 20 to 50 degrees. The charged particles may be passed through the first electric field and then through the second electric field when the intermediate electrode has a voltage applied thereto such that the waveform of the magnitude of the second electric field during the phase acceptance time period and the waveform of the magnitude of the first electric field during a corresponding time period offset from the phase acceptance time period have substantially equal waveform shapes.

[0017] In accordance with another aspect of the invention, there is provided an oscillating field particle accelerator for accelerating charged particles of a particle beam. The particle accelerator includes: (a) first electric field means for passing the charged particles from a source of the charged particles toward an intermediate electrode disposed within the particle accelerator; (b) second electric field means for passing the charged particles from the intermediate electrode toward a second electrode of the particle accelerator; and (c) beam focusing means for reducing divergence of the beam by the first electric field means having a magnitude less than a peak magnitude of the second electric field means.

[0018] The magnitude of the first electric field may be less than or equal to a minimum magnitude of the second electric field occurring during a phase acceptance time period associated with a phase acceptance of the particle accelerator.

[0019] In accordance with another aspect of the invention, there is provided a kit for reducing divergence of a beam of charged particles in an oscillating field particle accelerator. The kit includes an intermediate electrode dimensioned for installation within the particle accelerator between a source of the charged particles and a second electrode of the particle accelerator; and instructions for exposing the charged particles to a first electric field extending between the source and the intermediate electrode prior to being exposed to a second electric field extending between the intermediate electrode and the second electrode, the magnitude of the first electric field being less than a peak magnitude of the second electric field.

[0020] In accordance with another aspect of the invention, there is provided an improved oscillating field particle accelerator. The improved particle accelerator includes an intermediate electrode disposed within the particle accelerator between an ion source associated with the particle accelerator and a second electrode of the particle accelerator, the magnitude of a first electric field caused by the intermediate electrode being less than the peak magnitude of a second electric field caused by the second electrode.

[0021] The particle accelerator may be a circular particle accelerator. The particle accelerator may be a cyclotron. The particle accelerator may be a linear accelerator.

[0022] The ion source may be operable to produce charged particles for forming a particle beam. The ion source may be internal to the particle accelerator. A first region may be defined within the particle accelerator. The first region may be defined between the ion source and the intermediate electrode. The ion source may be an external ion source. The ion source may be a stand-alone ion source. The ion source may be connected to the particle accelerator. The particle accelerator may include a connection for receiving the ion source. The first region may be defined between the connection and the intermediate electrode. The particle beam may travel within the particle accelerator.

[0023] The particle accelerator may include an intermediate electrode voltage source for applying an intermediate electrode voltage to the intermediate electrode. The intermediate electrode voltage may be a fixed voltage. The intermediate electrode voltage may be a direct current (DC) voltage. The intermediate electrode voltage may be a time-varying voltage. The intermediate electrode voltage may be an alternating current (AC) voltage or portion thereof. The intermediate electrode voltage may be a pulsed voltage. The intermediate electrode voltage may effect an impulse. The intermediate electrode may be operable to cause the first electric field within the first region. The first electric field may subsist between the ion source and the intermediate electrode. The first electric field may subsist between the connection and the intermediate electrode. The first electric field may subsist within the first region. The first electric field may be caused by the intermediate electrode. The first electric field may be caused by the intermediate voltage. The first electric field may be caused by the intermediate voltage when applied to the intermediate electrode. The intermediate electrode may have a substantially planar shape. The intermediate electrode may be aligned transversely to the direction of travel within the particle accelerator of the particle beam. The intermediate electrode may define an intermediate aperture for permitting beam particles to pass through the intermediate electrode. Beam particles passing through the intermediate electrode may pass through the intermediate aperture of the intermediate electrode. The intermediate aperture may have a rectangular shape. The intermediate aperture may have an elongated shape. The intermediate aperture may form an intermediate aperture slit. The intermediate aperture may be vertically oriented. The intermediate electrode may be ring-shaped. The intermediate electrode may be tube-shaped. The intermediate electrode may form an open-ended cylinder. The intermediate aperture may have a substantially circular cross-section. The first electric field may subsist within the intermediate aperture. The first region may be defined as the volume within the intermediate aperture. Beam particles passing through the intermediate electrode may pass from the intermediate region into a second region.

[0024] The second region may be defined within the particle accelerator. The second region may be defined between the intermediate electrode and the second electrode. The second electric field may subsist within the second region. The second electrode may be an extraction electrode. The second electrode may be a final electrode. The second electrode may be a radio frequency resonator electrode. The particle accelerator may include a second electrode voltage source for applying a second electrode voltage to the second electrode. The second electrode voltage may be a fixed voltage. The second electrode voltage may be a direct current (DC) voltage. The second electrode voltage may be a time-varying voltage. The second electrode voltage may be an alternating current (AC) voltage or portion thereof. The second electrode voltage may be a pulsed voltage. The second electrode voltage may effect an impulse.

[0025] The second electrode may be operable to cause the second electric field within the second region. The second electric field may subsist between the intermediate electrode and the second electrode. The second electric field may subsist within the second region. The second electric field may be caused by the second electrode. The second electric field may be caused by the second electrode voltage. The second electric field may be caused by the second electrode voltage when applied to the second electrode. The second electrode may have a substantially planar shape. The second electrode may be aligned transversely to the direction of travel within the particle accelerator of the particle beam. The second electrode may define a second aperture for permitting beam particles to pass through the second electrode. Beam particles passing through the second electrode may pass through the second aperture of the second electrode. The second aperture may have a rectangular shape. The second aperture may have an elongated shape. The second aperture may form a second aperture slit. The second aperture may be vertically oriented. The second electrode may be ring-shaped. The second electrode may be tube-shaped. The second electrode may form an open-ended cylinder. The second aperture may have a substantially circular cross-section. The second electric field may subsist within the second aperture. The second region may be defined as the volume within the second aperture. Beam particles passing through the second electrode may pass from the second region into a remaining portion of the particle accelerator. The remaining portion may be a main body of the particle accelerator. Beam particles passing through the second electrode may pass from the second region into a longitudinal non-accelerating region.

[0026] The first electric field may have a magnitude that is a fraction of the peak magnitude of the second electric field. The first electric field may have a peak magnitude that is less than the peak magnitude of the second electric field. The first electric field may have an instantaneous magnitude that is at all times less than the instantaneous magnitude of the second electric field. The first electric field may have an average magnitude that is less than the peak magnitude of the second electric field. The first electric field may have a root mean square magnitude that is less than the peak magnitude of the second electric field. The first electric field may have a root mean square magnitude that is less than the peak magnitude of the second electric field. The first electric field may have a peak magnitude that is less than the average magnitude of the second electric field. The first electric field may have a peak magnitude that is less than the root mean square magnitude of the second electric field. The first electric field may have a peak magnitude that is less than the root mean square magnitude of the second electric field. The first electric field may have an average magnitude that is less than the average magnitude of the second electric field. The first electric field may have a root mean square magnitude that is less than the root mean square magnitude of the second electric field. The intermediate electrode voltage may have a magnitude that is a fraction of the peak magnitude of the second electrode voltage. The intermediate electrode voltage may have a peak magnitude that is less than the peak magnitude of the second electrode voltage. The intermediate electrode voltage may have an instantaneous magnitude that is at all times less than the instantaneous magnitude of the second electrode voltage. The intermediate electrode voltage may have an average magnitude that is less than the peak magnitude of the second electrode voltage. The intermediate electrode voltage may have a root mean square magnitude that is less than the peak magnitude of the second electrode voltage. The intermediate electrode voltage may have a peak magnitude that is less than the average magnitude of the second electrode voltage. The intermediate electrode voltage may have a peak magnitude that is less than the root mean square magnitude of the second electrode voltage. The intermediate electrode voltage may have an average magnitude that is less than the average magnitude of the second electrode voltage. The intermediate electrode voltage may have a root mean square magnitude that is less than the root mean square magnitude of the second electrode voltage.

[0027] The particle accelerator may be operable to extract charged particles from the ion source. The particle accelerator may be operable to receive beam particles into the first region from the ion source. The particle accelerator may be operable to receive beam particles into the first region from a longitudinal non-accelerating region of the particle accelerator. The particle accelerator may be operable to accelerate beam particles through the first region. The particle accelerator may be operable to accelerate beam particles through the first electric field. The particle accelerator may be operable to cause beam particles to pass through the intermediate aperture. The particle accelerator may be operable to accelerate beam particles through the second region. The particle accelerator may be operable to accelerate beam particles through the second electric field. The particle accelerator may be operable to cause beam particles to pass through the second electrode aperture. The particle accelerator may be operable to cause beam particles to pass through the second electrode aperture so as to form an output particle beam within the particle accelerator. The output particle beam may be a non-diverging beam. The output particle beam may be a particle beam of reduced divergence. The output particle beam may be a converging beam.

[0028] In accordance with another aspect of the invention, there is provided a method of reducing divergence of a particle beam in an oscillating field particle accelerator, the method comprising accelerating particles of the particle beam through a first electric field caused by an intermediate electrode disposed within the particle accelerator between an ion source associated with the particle accelerator and a second electrode of the particle accelerator, and accelerating the particles through a second electric field caused by the second electrode and having a peak magnitude greater than the magnitude of the first electric field.

[0029] Accelerating particles of the particle beam through a first electric field caused by an intermediate electrode disposed within the particle accelerator between an ion source associated with the particle accelerator and a second electrode of the particle accelerator may involve accelerating the particles through a first region defined as the volume between the ion source and the intermediate electrode. The method may further involve passing the particles through an intermediate aperture of the intermediate electrode. Accelerating particles of the particle beam through a first electric field caused by an intermediate electrode disposed within the particle accelerator between an ion source associated with the particle accelerator and a second electrode of the particle accelerator may involve accelerating the particles through a first region defined as the volume within the intermediate electrode. Accelerating particles of the particle beam through a first electric field caused by an intermediate electrode disposed within the particle accelerator between an ion source associated with the particle accelerator and a second electrode of the particle accelerator may involve accelerating the particles through the intermediate electrode. Accelerating the particles through a second electric field caused by the second electrode and having a peak magnitude greater than the magnitude of the first electric field may involve accelerating the particles through a second region defined as the volume between the intermediate electrode and the second electrode. The method may further involve passing the particles through a second electrode aperture of the second electrode. Accelerating the particles through a second electric field caused by the second electrode and having a peak magnitude greater than the magnitude of the first electric field may involve accelerating the particles through a second region defined as the volume within the second electrode. Accelerating the particles through a second electric field caused by the second electrode and having a magnitude greater than the magnitude of the first electric field may involve accelerating the particles through the second electrode.

[0030] In accordance with another aspect of the invention, there is provided a use of the intermediate electrode in the particle accelerator.

[0031] In accordance with another aspect of the invention, there is provided a kit for retrofitting an oscillating field particle accelerator. The kit includes an intermediate electrode dimensioned for being installed within the particle accelerator between an ion source associated with the particle accelerator and a second electrode of the particle accelerator, the intermediate electrode being connectable to an intermediate electrode voltage source such that a first electric field caused by the intermediate electrode has a lower magnitude than the peak magnitude of a second electric field caused by the second electrode. The kit may include the intermediate electrode voltage source.

[0032] Other aspects and features of the present invention will become apparent to those of ordinary skill in the art upon review of the following description of embodiments of the invention in conjunction with the accompanying figures and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0033] In drawings which illustrate by way of example only embodiments of the invention:

[0034] FIG. **1**A is a schematic representation of a prior art single-gap configuration, showing a particle beam diverging after exiting the prior art configuration;

[0035] FIG. **1**B is a schematic representation of a dual-gap configuration according to an embodiment of the invention, showing reduced divergence of the particle beam after exiting the configuration;

[0036] FIG. **2**A is a plan view of a prior art cyclotron, showing a diverging beam;

[0037] FIG. **2**B is a plan view of a cyclotron having an intermediate electrode according to one embodiment of the invention;

[0038] FIG. **3** is a graphical representation of the magnitudes of first and second electric fields in the cyclotron of FIG. 2B, showing electric field magnitudes for accelerating negatively charged particles;

[0039] FIG. **4** is a graphical representation of the magnitudes of the first and second electric fields in the cyclotron of FIG. **2**B, showing electric field magnitudes for accelerating positively charged particles;

[0040] FIG. **5**A is a schematic representation of simulation results for the prior art cyclotron shown in FIG. **2**A, showing a diverging beam; and

[0041] FIG. **5**B is a schematic representation of simulation results for the cyclotron of FIG. **2**B, showing a beam of reduced divergence.

DETAILED DESCRIPTION

[0042] An oscillating field particle accelerator for accelerating charged particles of a particle beam includes: (a) first electric field means for passing the charged particles from a source of the charged particles toward an intermediate electrode disposed within the particle accelerator; (b) second electric field means for passing the charged particles from the intermediate electrode toward a second electrode of the particle accelerator; and (c) beam focusing means for reducing divergence of the beam by the first electric field means having a magnitude less than a peak magnitude of the second electric field means.

[0043] The apparatus in at least one embodiment of the invention includes an intermediate accelerating electrode to decrease the divergence of particle beams generated by electric fields in particle accelerators such as cyclotrons.

[0044] Referring to FIG. **1**A and by way of explanation, beams **10** of charged particles extracted from ion sources **12** having an ion source wall **14** with an ion source aperture **16** therein and accelerated with a prior art single-gap extraction electrode **18** toward its extraction aperture **20** via the single gap **22** are always divergent (i.e. the single-gap electric field **24**, illustrated in FIG. **1**A by the solid arrow, resulting from the voltage difference between the voltage of the ion source **12** and the voltage of the extraction electrode **18** forms a lens with a negative focal length). This divergence of the particle beam **10** envelope exiting through the extraction aperture **20** of the extraction electrode **18** frequently leads to unwanted particle beam loss in a particle accelerator.

[0045] For ease of illustration, FIG. **1**A shows the single-gap electric field **24** in the same direction as the general direction of movement of the charged particles from the ion source **12** toward the extraction electrode **18**, as occurs in the case where the charged particles are positively charged, the ion source wall **14** is at ground potential and the extraction electrode **18** is at a negative potential. As is known in the art, the single-gap electric field **24** will have the opposite polarity (not shown) to accelerate negatively charged particles from the ion source **12** toward the extraction electrode **18** in a manner analogous to that shown in FIG. **1**A.

[0046] FIG. **1**A also shows single-gap constant-voltage contours **26** as dashed lines of constant voltage within the single gap **22** extending between the ion source wall **14** and the extraction electrode **18**. As illustrated in FIG. **1**A, the single-gap electric field **24** accelerates the charged particles of the beam **10** across the single gap **22** along a trajectory which is generally perpendicular to the single-gap constant-voltage contours **26**. As also shown in FIG. **1**A, the single-gap constant-voltage contours **26** bend near the extraction aperture **20**. The single-gap electric field **24** is a vector quantity having a magnitude which may be approximately calculated as the absolute difference between the voltage at the extraction electrode **18** and the voltage at the ion source wall **14**, divided by the scalar distance of the single gap **22** extending between the extraction electrode **18** and the ion source wall **14**. In a particular example in which the extraction aperture **20** has a circular cross-section and the transit time of the beam **10** charged particles across the single gap **22** is negligibly small compared to the time period of the sinusoidally varying single-gap electric field **24**, the single-gap focal length may be approximated as follows:

$$f_{single\text{-}gap} \cong \frac{-4V_0}{\vec{E}_0} = -4g_0$$

[0047] where

[0048] $f_{single\text{-}gap}$ is the single-gap focal length of the prior art configuration shown in FIG. **1**A;

[0049] V_0 is the voltage on the single-gap extraction electrode **18**;

[0050] E_0 is the single-gap electric field **24**; and

[0051] g_0 is the single gap **22** distance between the ion source wall **14** and the extraction electrode **18**.

[0052] As can be seen by the approximation formula, the single-gap focal length is negative (due to the single gap **22** distance being a positive scalar value) and hence the beam **10** is a diverging beam **10** as illustrated in FIG. **1**A.

[0053] In contrast to the prior art device of FIG. **1**A, FIG. **1**B shows an intermediate electrode **28** in accordance with an embodiment of the invention placed between the ion source **12** and the final particle beam extraction electrode **18**, and voltages are applied to the electrodes **18** and **28** and to the ion source **12** at its wall **14** such that when the magnitude of the first-gap electric field **30** (voltage difference/electrode separation) extending between the intermediate electrode **28** and the ion source wall **14** is less than the magnitude of the second-gap electric field **32** extending between the intermediate electrode **28** and the extraction electrode **18**, then the composite lens (i.e. dual acceleration gap **40** configuration) can have a positive focal length and the particle beam divergence is reduced and, with proper parameters, focused through the beam limiting aperture **34** of the intermediate electrode **28** and the beam limiting aperture **20** of the extraction electrode **18**. The amount of focusing/defocusing from the lens of the present invention depends on many parameters including, beam **10** energy, voltages on the electrodes **18** and **28**, separation distance of the first gap **36** extending between the ion source wall **14** and the intermediate electrode **28**, separation distance of the second gap **38** extending between the intermediate electrode **28** and the extraction electrode **18**, dimensions of the intermediate electrode aperture **34**, and the dimensions of the extraction electrode aperture **20**. Implementation of this invention includes appropriately adding the intermediate electrode **28** with appropriate voltages, given electrode separations and aperture dimensions so as to achieve particle beam focusing after crossing the dual acceleration gap **40** formed by the first gap **36** and the second gap **38** within a particle accelerator (not shown in FIG. **1**B). The focusing principle is general and, in fact, can be applied to particle accelerators other than cyclotrons. Even though the accelerator gaps used in prior art linear accelerators (LINACs) do, in fact, have a weak, net, positive-focusing force, the focusing can be made even stronger with an intermediate electrode **28** in accordance with an embodiment of the invention that produces a particle beam **10** with smaller transverse dimensions at and exiting from the aperture **20** of the final accelerating electrode **18**.

[0054] The ion source **12** shown in FIG. **1**B may in general be any source of charged particles, including any source of positively charged particles and any source of negatively charged particles, and the particle beam **10** may in general be a beam **10** of any type of charged particles, including ions or other positively or negatively charged particles.

[0055] The first-gap electric field **30** and the second-gap electric field **32** are shown in FIG. **1**B as having a polarity suitable for accelerating positively charged particles from the ion source **12** toward the extraction electrode **18** (via the intermediate electrode **28**). The first- and second-gap electric fields **30** and **32** will have the opposite polarity (not shown) when accelerating negatively charged particles in an analogous manner from the ion source **12** toward the extraction electrode **18**.

[0056] FIG. **1**B shows first-gap constant-voltage contours **42** as dashed lines of constant voltage within the first gap **36**, and second-gap constant-voltage contours **44** as dashed lines of constant voltage within the second gap **38**. As illustrated in FIG. **1**B, the first-gap electric field **30** accelerates the charged particles of the beam **10** across the first gap **36** in a direction which is generally perpendicular to the first-gap constant-voltage contours **42**, and the second-gap electric field **32** accelerates the charged particles of the beam **10** across the second gap **38** along a trajectory which is generally perpendicular to the second-gap constant-voltage contours **44**. As also shown in FIG. **1**B, the first-gap constant-voltage contours **42** bend near the intermediate electrode aperture **34**, and the second-gap constant-voltage contours **44** bend near the intermediate electrode aperture **34** and near the extraction aperture **20**. The first-gap electric field **30** is a vector quantity having a magnitude which may be approximately calculated as the absolute difference between the voltage at the intermediate electrode **28** and the voltage at the ion source wall **14**, divided by the scalar distance of the first gap **36** extending between the ion source wall **14** and the intermediate electrode **28**. Similarly, the second-gap electric field **32** is a vector quantity having a magnitude which may be defined generally as the absolute difference between the voltage at the extraction electrode **18** and the voltage at the intermediate electrode **28**, divided by the scalar distance of the second gap **38** extending between the intermediate electrode **28** and the extraction electrode **18**.

[0057] The first and second gaps **36** and **38** shown in FIG. **1**B form a dual acceleration gap **40**. In a particular example in which the intermediate electrode aperture **34** and the extraction aperture **20** each have a circular cross-section, the space adjacently following the extraction electrode **18** (shown in FIG. **1**B as being the illustrated area to the right of the extraction electrode **18**) has an electrical potential of zero, and the transit time of the beam **10** charged particles across the second gap **38** is negligibly small compared to the time period of the exemplary sinusoidally varying second-gap electric field **32**, the dual-gap focal length may be approximated as follows:

$$f_{dual\text{-}gap} \cong 4g_1 * \left(\frac{\vec{E}_1}{\vec{E}_2 - \vec{E}_1}\right) = \frac{4V_1}{\left(\frac{V_2 - V_1}{g_2}\right) - \left(\frac{V_1}{g_1}\right)}$$

[0058] where

[0059] $f_{dual\text{-}gap}$ is the dual-gap focal length of the dual acceleration gap **40** configuration shown in FIG. **1**B;

[0060] V_1 is the voltage on the intermediate electrode **28**;

[0061] $\vec{E}_1$ is the first-gap electric field **30**;

[0062] g_1 is the first gap **36** distance between the ion source wall **14** and the intermediate electrode **28**;

[0063] V_2 is the voltage on the extraction electrode **18**; and

[0064] $\vec{E}_2$ is the second-gap electric field **32**; and

[0065] g_2 is the second gap **38** distance between the intermediate electrode **28** and the extraction electrode **18**.

[0066] As can be seen by the dual-gap approximation formula, the dual-gap focal length can be made positive by appropriately selecting parameters of the intermediate electrode **28**, such as its location (indicated by the separation distances of the first and second gaps **36** and **38**) and its voltage (so as to effect an appropriate relationship between the first-gap electric field **30** and the second-gap electric field **32**), thereby causing convergence and/or reducing divergence of the beam **10** as shown in FIG. **1**B.

[0067] By way of further explanation and with reference to FIG. **2**A showing a prior art cyclotron type particle accelerator **46**, particle accelerators in general require particle beam **10** focusing during the acceleration process to avoid particle beam **10** loss. Focusing is achieved by using electric and/or magnetic fields to alter the trajectory of particles in a beam **10** in a manner having similarities or analogies with optical lenses and light rays. In a particular example, cyclotrons depend on radial focusing (usually formulated as a focusing frequency, v_r, because the focusing is periodic for most of the cyclotron) and vertical focusing (e.g. by frequency v_z) of particles in the accelerated beams. At outer regions **48** within a prior art cyclotron **46** where higher beam **10** energies occur in a cyclotron **46**, the focusing (vertical and radial) is dominated by appropriate variations of the magnetic field and the electric field focusing is negligible in comparison. However, at or near the centre **50** of the cyclotron **46** where the beam **10** energy is low, the vertical focusing from variations of the magnetic field is small. Within the central region **50** of the cyclotron, the electric field focusing dominates and is necessary to preserve the particle beam properties. In prior art cyclotrons **46** with an internal ion source, the charged particles of the particle beam **10** are extracted through a small aperture in the ion source **12** across a single gap **22** to the ion 'puller' or extraction electrode **18**. Usually, the extraction electrode **18** forms part of a radio frequency resonator at high voltage potential such that a time-varying voltage, such as an RF voltage, is applied to the extraction electrode **18**. The single-gap electric field **24** across the single gap **22** between the ion source **12** and the 'puller' or extraction electrode **18** forms an electrostatic lens with a negative focal length (i.e; it is defocusing). The defocused beam **10** is shown in FIG. **2**A as having a diverging line width to graphically represent such defocusing. The single-gap electric field **24** extracting charged particles from the ion source **12** is usually increased, with the use of electrode 'posts' **52** (to better define the beam exit aperture **20** of the extraction electrode **18**) at the accelerating electrode (cyclotron 'dee') (i.e. extraction electrode **18**). That is, the extraction electrode **18** may be implemented as a pair of vertical posts **52** located on opposing sides of the beam **10** path. However, in prior art cyclotrons this electrode **18** increases both the radial and vertical divergences of the beam **10** (decreases the v_r and v_z). FIG. **2**A shows the gaps between the four 'dee' sections of the prior art cyclotron **46** as being bounded by dashed lines **54**. The term 'dee' arose historically from the use of two D-shaped sections in the prior art cyclotron **46**. Between each 'dee' section is a 'dee' gap **55**, one of which is the single gap **22**. The 'dee' gap **55** that the beam **10** first encounters upon exiting the ion source **12** within the prior art cyclotron **46** is the single gap **22** disposed between the ion source **12** and the extraction electrode **18**. Subsequent 'dee' gaps **55** which the beam **10** encounters after exiting the single gap **22** are visible in FIG. **2**A. The beam **10** path in a prior art cyclotron **46** is spiral in shape such that the charged particles of the beam **10** encounter the subsequent 'dee' gaps **55** multiple times. Typically, electrode 'posts' **52** are only used in the central region **50** of the cyclotron **46** for at most the first few turns of the beam **10** and are not used in the outer region **48** of the prior art cyclotron **46**.

[0068] Some prior art stand-alone (i.e. not internal to an oscillating field particle accelerator) ion beam extraction systems (i.e. ion sources) (not shown) include an intermediate electrode (not shown), in an 'accel-acce' configuration (not shown) used to vary the focal properties of the ion beam extraction system (i.e. ion source) (not shown) to provide a beam at the exit of its extraction electrode (not shown) with smaller radial extent and less angular divergence. However, such prior art 'accel-acce' configurations of stand-alone ion sources are limited to internal configurations of such stand-alone ion sources. A major innovation of the present invention includes applying principles of what is sometimes done within stand-alone ion source extraction systems (i.e. within ion sources) for other applications (not shown) to create novel and inventive first turn dual accelerating gaps **40** in oscillating field particle accelerators such as cyclotrons and other novel and inventive dual acceleration gap **40** configurations of oscillating field particle accelerators.

[0069] In contrast to the prior art configuration of FIG. **2**A, FIG. **2**B shows the cyclotron **56** according to an embodiment of the invention in which, for example, the intermediate electrode **28** is placed between the 'puller' or extraction electrode **18** and the ion source **12**. The ion source **12** is shown in FIG. **2**B as being an internal source which is internal to the particle accelerator **56** of FIG. **2**B. In conjunction with appropriate separation and applied voltage in accordance with an embodiment of the invention, then the focal length can be positive and the particle beam **10** is focused. The ability to better focus the beam in accordance with an embodiment of the invention has several positive consequences. Beam loss is reduced. Erosion of electrodes by beam loss is reduced. Life time of cyclotron components increases because of the reduction of beam loss. The total accelerated current increases. The improved focusing of the beam **10** in accordance with the present invention is represented graphically in FIG. **2**B by a narrow line width of the beam **10**.

[0070] FIG. **2**B also shows the first gap **36**, between the ion source **12** and the intermediate electrode **28**, and the second gap **38**, between the intermediate electrode **28** and the extraction electrode **18**, which together form the dual acceleration gap **40**. The 'dee' gaps **55**, one of which is the dual acceleration gap **40**, between the four 'dee' sections of the cyclotron **56** are shown in FIG. **2**B as being bounded by the dashed lines **54**. The extraction electrode **18** may be implemented as electrode posts **52**, as shown in FIG. **2**B. While FIG. **2**B shows four 'dee' gaps **55** between four 'dee' sections, the present invention is suitable for implementation within cyclotrons and other oscillating field particle accelerators having any number of 'dee' sections and any number of electrode posts **52**.

[0071] While not shown in the Figures, additional or alternative instances of the intermediate electrode **28** of the present invention may be implemented between a point of entrance of the beam **10** into a given 'dee' gap **55** and an electrode post **52** located at the beam **10** exit from the given 'dee' gap **55**, thereby forming a dual acceleration gap **40** configuration in accordance with embodiments of the invention which is subsequent to the dual acceleration gap **40** shown in FIG. **2**B.

[0072] Referring back to FIG. **2**A, another issue in prior art cyclotrons **46** is that the time required for charged particles to transit the 'dee' gap, including the single gap **22** (i.e. the time if takes for particles in a beam to reach full energy after having traveled an effective distance within the 'dee' gap, including the single gap **22**) limits the useable extraction voltage and as the extracted current is proportional to $(\text{Voltage})^{3''2}$, the maximum current that can be accelerated is correspondingly limited.

[0073] Referring again to FIG. **2**B, the introduction of an intermediate electrode **28** into a cyclotron **56** in accordance with an embodiment of the invention, for example, will result in higher accelerated currents associated with the beam **10** of charged particles.

[0074] Referring back to FIGS. **1**A and **2**A, in prior art cyclotrons **46** with external ion sources (not shown in the Figures), a low energy beam **10** is transported to the centre or central region **50** of the prior art cyclotron **46** and bent into the median plane of the prior art cyclotron **46** at an appropriate radius and at a position to be accelerated across a single gap **22** by a single-gap electric field **24** produced by the extraction electrode **18** which can be, for example, a radio frequency resonator electrode **18**. As with prior art cyclotrons **46** (FIG. **2**A) with internal ion sources **12**, the single-gap electric field **24** in this single gap **22** is usually enhanced with the use of 'posts' **52** to decrease the transit time to higher voltage (i.e. to full energy) of charged particles injected into the prior art cyclotron **46**. The electrostatic lens formed at this single gap **22** generally has a negative focal length in prior art cyclotrons **46**, especially prior art cyclotrons **46** with external ion sources (not shown).

[0075] Referring again to FIG. **2**B, an appropriately designed intermediate electrode **28** in accordance with an embodiment of the invention would advantageously decrease the divergence following the acceleration.

[0076] Another potential application of this technique is to the gaps of LINACs (not shown) accelerating charged particles.

[0077] In prior art LINACs (not shown) the particles traverse a linear path in which the particles leave a region of negligible electric field, pass through a collinear gap with high electric field and enter a collinear region with negligible electric field. It is well established and can be calculated for circular apertures, of similar dimensions, that the net effect of such linearly extending accelerating gap is weak focusing. Prior art LINACs require additional focusing elements to maintain a beam within desired dimensions.

[0078] In contrast to the prior art LINACs and with reference to FIG. **1**B, the introduction of an appropriate intermediate electrode **28** in accordance with an embodiment of the invention in the dual acceleration gap **40** can reduce the transverse size of the beam **10** at the final extraction electrode **18** and thereby enhance the focusing properties of these dual accelerating gaps **40**. The increased focusing would advantageously reduce the need for as many expensive focusing elements as are currently used with existing LINACs and consequently also advantageously reduce the required foot print of the LINAC accelerator.

[0079] Referring back to FIG. **1**A, ions or charged particles are accelerated as beams **10** of particles by particle accelerators. Just as is the case for light beams where optical lenses are used to confine photons in the beams to useable dimensions, the charged particles in particle beams **10** must be regularly focused with the fields from magnetic and electric devices, to confine the particle beams to manageable dimensions. Ions, or charged particles, are created in ion sources such as the ion source **12**. The lens properties of electric and magnetic devices are defined in a manner similar or analogous to optics lenses. Ions, or charged particles, are created in ion sources such as the ion source **12**, extracted from the ion source to form particle beams **10** and then further accelerated. When the charged particles are extracted from an ion source **12** with a small aperture **16** (planar diode) with a single-gap extraction electrode **18**, as in known in the prior art, the resultant beam **10** is always defocusing (see FIG. **1**A). For circular apertures **16** and **20**, the focal length (f) can be calculated to be about −4g0, where g0 is the distance between the electrodes **14** and **18** for this geometry. This divergence (defocusing because f is always negative for this single-gap electrode arrangement) frequently leads to particle beam loss in the accelerator (not shown in FIG. **1**A).

[0080] In contrast to the prior art single-gap configuration of FIG. **1**A, if an intermediate electrode **28** as shown in FIG. **1**B in accordance with an embodiment of the invention is placed between the ion source **12** and the final acceleration (extraction) electrode **18**, and voltages are applied to the electrodes **28** and **18** and the ion source wall **14** such that that the first-gap electric field **30** strength (voltage difference/electrode separation) between the intermediate electrode **28** and the ion source wall **14** is less than the second-gap electric field **32** strength between the intermediate electrode **28** and the extractor or extraction electrode **18**, then the beam **10** can advantageously be focussed or have reduced defocusing.

[0081] FIG. **1**B shows schematically this type of electrode arrangement in accordance with an embodiment of the invention. In this case the focal length (with some simplifying assumptions) can be calculated to be about $4V_f/(E_{exit}-E_{entrance})$, where V_f is the voltage gain, E_{exit} is the electric field in the second gap **38** with a gap **38** distance of g2, and $E_{entrance}$ is the electric field at the entrance of the dual acceleration gap **40** (i.e. in the first gap **36**) having a gap **36** distance of g1. The intermediate electrode **28** position and voltage can be varied to realize a wide range of ratios for $E_{exit}/E_{entrance}$, the aperture dimensions of the ion source aperture **16**, intermediate electrode aperture **34** and the extraction aperture **20** can be arranged to be consistent with beam transverse dimensions, and thereby change the focal length from being positive to negative or vice versa. The typical cyclotron apertures (not shown in FIG. **1**B) are rectangular, or otherwise oblong, and not circular. The equations for calculating dual-gap focal length in the case of rectangular or otherwise oblong apertures are more complicated but the focusing/defocusing principle remains the same. The structure described above in relation to embodiments of the invention shows how intermediate electrodes **28** with selected voltages applied thereto can be used to manipulate the focal properties of particle beams **10** in a variety of different particle accelerators (not shown in FIG. **1**B), including to advantageously reduce beam divergence of beams **10** exiting dual acceleration gaps **40** as shown in FIG. **1**B.

[0082] As noted above and with reference to FIGS. **1**A and **2**A, accelerators require particle beam **10** focusing during the acceleration process to avoid beam **10** loss. In a particular example, prior art cyclotrons **46** depend on radial (usually formulated as a focusing frequency and given the symbol, v_r) and vertical focusing (v_z) of particles in the accelerated beams. At outer regions **48** within a prior art cyclotron **46** where higher beam **10** energies occur, the beam **10** focusing in a prior art cyclotron **46** is dominated by appropriate variations of the magnetic field and the electric field focusing is negligible in comparison. However at or near the centre **50** of the prior art cyclotron **46** the radial focusing from variations of the magnetic field is small and the electric field focusing dominates.

[0083] FIG. **2**A schematically shows some of the critical elements found in a prior art cyclotron **46** with an internal ion source **12**. In prior art cyclotrons **46**, the defocusing problem is usually reduced with the use of electrode posts **52** (referred to as a 'puller' or extraction electrode **52**) at the entrance and exit of the 'dee' gap **55** where the beam **10** is accelerated. This is valid for both prior art cyclotrons **46** with internal ion sources **12** and for prior art cyclotrons **46** with external ion sources (not shown). Nevertheless, even with these 'posts' **52**, including the extraction electrode **18**, the particle beam **10** entering the 'dee' electrode subsequent to exiting the single gap **22** remains radially defocusing in a prior art cyclotron **46**.

[0084] Referring again to FIG. **2**B, an intermediate electrode **28** in accordance with an embodiment of the invention is placed between the 'puller' or extraction electrode **18** and the ion source **12** (or inflector for external ion sources, not shown), with appropriate separation and applied voltage, then the beam **10** advantageously becomes better focused. This technique of embodiments of the invention is suitable for use in cyclotrons **56** with internal ion sources **12** and at the early acceleration gaps (e.g. dual acceleration gaps **40**) for cyclotrons **56** with external ion sources (not shown), for example.

[0085] Still referring to FIG. **2**B, the consequences of being able to better focus the beam **10** through the puller or extraction electrode **18** in accordance with embodiments of the invention are beneficial and numerous. Beam **10** loss is reduced. More particles are accelerated. The particle accelerator of the present invention becomes potentially more efficient with less induced radio-activity which would otherwise result from beam **10** loss. Erosion of electrodes **18** by beam **10** loss is reduced. Life time of cyclotron **56** components increases because of the reduction of beam **10** loss. Beam **10** loss leads to activation of components, component heating, surface sputtering, and erosion of components with eventual component failure. In brief, the total accelerated current increases and the downtime due to beam **10** loss failures decreases.

[0086] Referring back to FIGS. **1**A and **2**A, another issue in prior art cyclotrons **46** is that the time required for particles to transit the 'dee' gap, including the single gap **22**, limits the maximum useable extraction voltage and, as the extracted current is proportional to (Voltage)$^{3/2}$, the maximum current that can be accelerated is correspondingly limited under existing schemes.

[0087] However, with reference to FIGS. **1**B and **2**B, this approach of the present invention results in the net transit time being advantageously reduced and the extraction voltage being advantageously higher. Implementing this invention involves adding this intermediate electrode **28** with appropriate voltages and electrode separations so to achieve particle beam focusing or reduced defocusing across the dual acceleration gap **40**. The focusing principle is general and, in fact, can be applied to dual accelerating gaps **40** of particle accelerators other than cyclotrons **56**.

[0088] Referring back to FIGS. **1**A and **2**A, the single accelerator gaps **22** used in prior art linear accelerators (LINACs) (not shown) do have a weak, net, positive-focusing force.

[0089] However, referring to FIG. **1**B, the focusing in a LINAC (not shown) can advantageously be made stronger with an intermediate electrode **28** in accordance with an embodiment of the invention that produces a smaller electric field in the first gap **36** compared to the electric field in the second gap **38**.

[0090] In a first embodiment of the invention and with reference to FIG. **1**B, an oscillating field particle accelerator (not shown in FIG. **1**B) includes an intermediate electrode **28** disposed between an internal ion source **12** and an extraction electrode **18** of the particle accelerator. The intermediate electrode **28** is formed of a planar sheet aligned transversely to the direction of travel of the particle beam **10**. There is an aperture **34** in the planar sheet through which the particle beam **10** may traverse. The aperture **34** may be a rectangular slit aperture, or otherwise be oblong in shape, may be circular or may have any suitable shape for example. There is a voltage source (not shown) applied to the intermediate electrode **28**, which may be a fixed, direct current (DC) voltage or may be a time-varying voltage. The magnitude of the first-gap electric field **30** between the ion source **12** and the intermediate electrode **28** is less than the peak magnitude of the second-gap electric field **32** between the intermediate electrode **28** and the extraction electrode **18**. The extraction electrode **18** is disposed further from the ion source **12** than is the intermediate electrode **28**, thus the extraction electrode **18** is a final electrode **18**. In a second embodiment of the invention, an oscillating field particle accelerator (not shown in FIG. **1**B) includes a connection to an external ion source (not shown) and includes an internal dual acceleration gap **40** having an input end connected to the external ion source and an output end defined by a final extraction electrode **18** from which a particle beam emerges into the remainder (e.g. main body) of the particle accelerator. In the second embodiment, an intermediate electrode **28** is disposed between the input and output ends of the internal dual acceleration gap **40** such that the intermediate electrode **28** is disposed between the connection to the external ion source (not shown) and the final electrode **18**. The intermediate electrode **28** is formed of a planar sheet aligned transversely to the direction of travel of the particle beam **10**. There is an aperture **34** in the planar sheet through which the particle beam **10** may traverse. The aperture **34** may be a rectangular slit aperture, or otherwise oblong in shape, may be circular or may have any suitable shape for example. There is a voltage source (not shown) applied to the intermediate electrode **28**, which may be a fixed, direct current (DC) voltage or may be a time-varying voltage. The magnitude of the first-gap electric field **30** between the input end and the intermediate electrode **28** is less than then the peak magnitude of the second-gap electric field **32** between the intermediate electrode **28** and the output end.

[0091] In a third embodiment of the invention analogously represented by FIG. **1**B, a linear particle accelerator (LINAC) (not shown) includes a sequence of longitudinally aligned tube-like or cylindrical electrodes. The cylindrical electrodes are longitudinally spaced apart so as to form linear acceleration gaps between adjacent electrodes. Charged particles are accelerated through these acceleration gaps by electric fields caused by voltage differences existing between adjacent cylindrical electrodes. In the third embodiment, an intermediate electrode, represented by analogy in FIG. **1**B by the intermediate electrode **28**, having a ring-like or tube-like structure is placed within a dual acceleration gap **40** so as to be longitudinally aligned with, spaced apart from, adjacent to and between an initial cylindrical electrode (typically at ground potential), represented in FIG. **1**B by the ion source wall **14**, and a final cylindrical electrode (typically having applied thereto a time-varying voltage), which is represented in FIG. **1**B by the extraction electrode **18**. The ring-like or tube-like structure of the intermediate electrode **28** defines a ring-shaped or tube-shaped intermediate aperture **34**. The intermediate aperture **34** may be cylindrical and have a circular cross-section. In the direction of travel of the beam particles through the linear accelerator (not shown), each intermediate electrode **28** precedes its corresponding final electrode **18** and is disposed between an ion source **12** associated with the linear accelerator and its corresponding final electrode **18**. In the direction of travel of the beam particles through the linear accelerator, one or more intermediate electrodes **18** may follow adjacently corresponding initial electrodes **14**. There is a voltage source applied to the intermediate electrode **28**, which may be a fixed, direct current (DC) voltage or may be a time-varying voltage. The voltage applied to the intermediate electrode **28** causes a first-gap electric field **30** to form between the immediately preceding initial electrode **14** and the intermediate electrode **28**. The magnitude of the first-gap electric field **30** is related to the voltage difference between the intermediate electrode **28** and its corresponding initial electrode **14**. A second-gap electric field **32** is formed between the intermediate electrode **28** and the immediately following final electrode **18**, and the magnitude of the second-gap electric field **32** is related to the voltage difference between the intermediate electrode **28** and its corresponding final electrode **18**. The magnitude of the first-gap electric field **30** is less than the peak magnitude of the second-gap electric field **32**.

[0092] Referring to FIGS. **3** and **4**, a sinusoidally time-varying second-gap electric field **32** is shown in accordance with exemplary embodiments of the invention. The second-gap electric field **32** shown in FIGS. **3** and **4** can be created by applying a sinusoidally time-varying voltage to the extraction electrode **18** (FIG. **2**B) of the dual accelerating gap **40** (FIG. **2**B), for example. In the exemplary embodiment of FIGS. **3** and **4**, and for ease of discussion, the ion source wall **14** is at ground potential (i.e. zero volts) relative to the intermediate electrode **28** (FIG. **2**B) and the extraction electrode **18** (FIG. **2**B).

[0093] FIG. **3** represents acceleration of negatively charged particles or ions, in which the first-gap electric field **30** has a positive value, such as may be caused by applying a positive direct current (DC) voltage to the intermediate electrode **28** (FIG. **2**B). On the other hand FIG. **4** represents acceleration of positively charged particles or ions, in which the first-gap electric field **30** has a negative value, such as may be caused by applying a negative DC voltage to the intermediate electrode **28** (FIG. **2**B). In general, the ion source wall **14** need not be at ground potential relative to the intermediate electrode **28** (FIG. **2**B) and the extraction electrode **18** (FIG. **2**B), provided the electrical potential of the intermediate electrode **28** is negative relative to electrical potential of the ion source wall **14** when accelerating positively charged ions and positive when accelerating negatively charged ions.

[0094] The exemplary phase acceptance of the embodiment of FIGS. **3** and **4** is 90 degrees (from −45 degrees to +45 degrees), as shown in FIGS. **3** and **4** by dashed lines **58**. While FIGS. **3** and **4** show the phase acceptance time period as being symmetrical about the occurrence in each cycle of the peak value **60** of the second-gap electric field **32**, in general the phase acceptance need not be precisely symmetrical with respect to the peak of the second-gap electric field **32** due to phase lagging or phase leading within the dual acceleration gap **40** configuration. Phase acceptance values other than 90 degrees are possible. For example, phase acceptance is typically in the range of 0 to 90 degrees, and may be in the range of 20 to 50 degrees. In some embodiments, the phase acceptance may be substantially equal to 36 degrees, which corresponds to a percentage acceptance of ten percent of the 360 degree cycle.

[0095] In the exemplary embodiments shown in FIGS. **3** and **4**, the magnitude of the first-gap electric field **30** is equal to the minimum magnitude of the second-gap electric field **32** occurring during the phase acceptance time period associated with the phase acceptance shown in FIGS. **3** and **4**. In variations of embodiments, the first-gap electric field **30** may have a magnitude which is less than (i.e. closer to zero) than the magnitudes of the second-gap electric field **32** for which charged particles will be accepted into the main body of the particle accelerator. Reducing the magnitude of the first-gap electric field **30** relative to the magnitude of the second-gap electric field **32** advantageously increases the focusing and/or decreases the defocusing of the beam **10** of charged particles. However, such reduction in the magnitude of the first-gap electric field **30** can cause a reduction in beam **10** current entering the main body of the particle accelerator. Thus, for some embodiments of the invention an optimal magnitude of the first-gap electric field **30** is equal to the minimum phase acceptance magnitude of the second-gap electric field **32**.

[0096] Further optimization of embodiments of the invention may be achieved by implementing a time-varying first-gap electric field **30**, albeit with the possibility of introducing additional variability in the beam **10** current of the beam **10** entering the main body of the particle accelerator. For example, a first-gap electric field **30** magnitude having a waveform offset from or otherwise corresponding to the second-gap electric field **32** magnitude waveform during phase acceptance can result in desired focusing characteristics of the beam **10** during phase acceptance. By way of example, a first-gap electric field **30** magnitude which is less than the second-gap electric field **32** magnitude by a constant offset magnitude during phase acceptance such that their respective waveform shapes match (not shown) during phase acceptance, albeit with an appropriate phase offset to account for beam **10** transit time through the dual acceleration gap **40** (FIG. **2**B), will advantageously result in a constant amount of focusing and/or a constant amount of the reduction in defocusing.

[0097] Referring to FIGS. **5**A and **5**B, comparative simulations of beam **10** dynamics have been performed by the inventor of the present invention and comparative simulation results are shown.

[0098] FIG. **5**A shows a plan view of a portion of a simulated prior art cyclotron **46** in which an ion source **12** and extraction electrode **18** form an initial acceleration single gap **22**. Upon exiting the single gap **22**, the beam **10** diverges such that a portion of the beam **10** is thereafter blocked when passing a first of subsequent pairs of electrode posts **52** associated with a first subsequent 'dee' gap **55**, such that only a limited and small beam **10** current is able to pass into the main body (not shown in FIG. **5**A) of the prior art cyclotron **46**. When FIG. **5**A shows divergence of the beam **10** in the plan view, a similar divergence occurs in the transverse plane as could be seen in a side view (not shown).

[0099] FIG. **5**B shows a plan view of a portion of a simulated cyclotron **56** having the intermediate electrode **28** positioned between the ion source **12** and the extraction electrode **18**, thereby forming the first gap **36** and the second gap **38** of the dual acceleration gap **40** configuration. Upon exiting the dual acceleration gap **40** configuration, the beam divergence is reduced such that less or no portion of the beam **10** is blocked by the first subsequent pair of electrode posts **52** associated with the first subsequent 'dee' gap **55**, thereby permitting a larger beam **10** current to pass into the main body of the cyclotron **56**. While FIG. **5**B shown reduced divergence of the beam **10** in the plan view in accordance with embodiments of the invention, a similar reduction in divergence occurs in such embodiments in the transverse plane as could be seen in a side view (not shown).

[0100] Thus, there is provided an oscillating field particle accelerator for accelerating charged particles, the particle accelerator comprising an intermediate electrode disposed within the particle accelerator between a source of the charged particles and a second electrode of the particle accelerator, the charged particles being exposed to a first electric field extending between said source and said intermediate electrode prior to being exposed to a second electric field extending between said intermediate electrode and said second electrode, the magnitude of said first electric field being less than a peak magnitude of said second electric field.

Method of Operation

[0101] With reference to FIGS. **1**B, **2**B, **3**, **4** and **5**B and the first embodiment of the invention, the internal ion source **12** produces ions or charged particles that form a particle beam **10**. Particles of the beam **10** are accelerated through a first region, such as the first gap **36** shown in FIGS. **1**B, **2**B and **5**B, defined between the ion source **12** and the intermediate electrode **28**, by a first-gap electric field **30** present in the first gap **36**. The first-gap electric field **30** is caused by a voltage applied to the intermediate electrode **28** such that a potential difference between the ion source wall **14** and the intermediate electrode **28** is created. At least some of the beam **10** particles pass from the first gap **36** through an aperture **34** in the intermediate electrode **28** into a second region, such as the second gap **38** shown in FIGS. **1**B, **2**B and **5**B, defined between the intermediate electrode **28** and the extraction electrode **18**. There is a second-gap electric field **32** in the second gap **38** which is caused by a voltage applied to the extraction electrode **18** such that a potential difference between the intermediate electrode **28** and the extraction electrode **18** is created. The beam **10** particles passing into the second gap **38** are accelerated by the second-gap electric field **32**. At least some of the beam **10** particles accelerated in the second gap **38** pass through an aperture **20** of the extraction electrode **18** to emerge into the remainder of the particle accelerator as an extracted particle beam **10**. By appropriately setting the voltage applied to the intermediate electrode **28** and the relative separation distances of the first and second gaps **36** and **38**, divergence of the extracted beam **10** can be reduced or eliminated, including causing the extracted beam **10** to converge.

[0102] With reference to FIGS. **1**B, **2**B, **3**, **4** and **5**B and the second embodiment of the invention, the external ion source (not shown) produces ions or charged particles that form a particle beam **10**. Particles of the beam **10** are received into the particle accelerator via a connection between the external ion source and the particle accelerator. Particles of the received beam **10** are accelerated through a first region, such as the first gap **36** shown in FIGS. **1**B, **2**B and **5**B, defined between the ion source **12** and the intermediate electrode **28**, by a first-gap electric field **30** present in the first gap **36**, in a manner analogous to that of the first embodiment. The remainder of the operation of the second embodiment of the invention is identical, similar or analogous to that of the corresponding operation of the first embodiment.

[0103] With reference to FIGS. **1**B, **2**B, **3**, **4** and **5**B and the third embodiment of the invention, the ion source associated with the linear accelerator (not shown) is typically an external ion source (not shown) that produces ions or charged particles in the form of a particle beam **10** received into the longitudinal chamber of the linear accelerator. Particles of the beam **10** are successively accelerated in longitudinally aligned acceleration gaps which, in the third embodiment, are configured as dual acceleration gaps **40** having an intermediate electrode **28**. Within each dual acceleration gap **40** of the third embodiment, beam **10** particles entering the acceleration gap are accelerated through a first region, such as the first gap **36** shown in FIGS. **1**B, **2**B and **5**B or another first gap analogous thereto, defined adjacent to and preceding the aperture of the ring-like or tube-like intermediate electrode **28** by a first-gap electric field **30** caused by an intermediate electrode **28** voltage applied to the intermediate electrode **28**, and then accelerated through a second region, such as the second gap **38** shown in FIGS. **1**B, **2**B and **5**B or another second gap analogous thereto, defined adjacent to and following the aperture **34** of the intermediate electrode **28** by a second-gap electric field **32** caused by the final extraction electrode **18**, before exiting the dual acceleration gap **40** into a subsequent non-acceleration region.

[0104] Accordingly in embodiments of the invention, the oscillating field particle accelerator receives ions or charged particles in the form of a particle beam from an ion source, passes the beam particles through a first electric field caused by an intermediate electrode of the particle accelerator, and then passes the beam particles through a second electric field caused by an electrode of the particle accelerator such that the particle beam emerging from the second electric field region is of reduced divergence or is a non-diverging particle beam, including a converging particle beam.

[0105] Thus, there is provided a method of reducing divergence of a beam of charged particles in an oscillating field particle accelerator, the method comprising passing the charged particles through a first electric field from a source of the charged particles toward an intermediate electrode disposed within the particle accelerator and then passing the charged particles through a second electric field from said intermediate electrode toward a second electrode of the particle accelerator when the magnitude of said first electric field is less than a peak magnitude of said second electric field.

[0106] While embodiments of the invention have been described and illustrated, such embodiments should be considered illustrative of the invention only. The invention may include variants not described or illustrated herein in detail. For example, the material of the intermediate electrode may be selected for achieving desired characteristics of the particle beam passing through the intermediate electrode or aperture thereof, including selecting the intermediate electrode material to be an electrically conductive material. Thus, the embodiments described and illustrated herein should not be considered to limit the invention as construed in accordance with the accompanying claims.

1. A cyclotron comprising an intermediate electrode disposed between a source of charged particles and a second electrode of the cyclotron, each of said source, said intermediate electrode and said second electrode being internal to the cyclotron, the charged particles being exposed to a first electric field extending between said source and said intermediate electrode prior to being exposed to a second electric field extending between said intermediate electrode and said second electrode, said second electrode having a time-varying voltage applied thereto such that said second electric field is time-varying, the magnitude of said first electric field being less than a peak magnitude of said second electric field.

2. The cyclotron of claim **1** wherein said intermediate electrode has a time-varying voltage applied thereto such that the magnitude of said first electric field is time-varying.

3. The cyclotron of claim **1** wherein said intermediate electrode has a DC voltage applied thereto such that the magnitude of said first electric field is substantially non-varying in time.

4. (canceled)

5. The cyclotron of claim **1** wherein said intermediate electrode defines an intermediate aperture for permitting the charged particles to pass through said intermediate electrode.

6-**9**. (canceled)

10. The cyclotron of claim **1** wherein the magnitude of said first electric field is less than or equal to a minimum magnitude of said second electric field occurring during a phase acceptance time period associated with a phase acceptance of the cyclotron.

11. (canceled)

12. The cyclotron of claim **10** wherein said phase acceptance is in a range of 20 to 50 degrees.

13. The cyclotron of claim **10** wherein said intermediate electrode has a voltage applied thereto such that the waveform of the magnitude of said second electric field during said phase acceptance time period and the waveform of the magnitude of said first electric field during a corresponding time period offset from said phase acceptance time period have substantially equal waveform shapes.

14. A method of reducing divergence of a beam of charged particles in a cyclotron, the method comprising passing the charged particles through a first electric field from a source of the charged particles toward an intermediate electrode and then passing the charged particles through a second electric field from said intermediate electrode toward a second electrode when said source, said intermediate electrode and said second electrode are internal to the cyclotron, when a time-varying voltage is being applied to said second electrode such that said second electric field is time-varying, and when the magnitude of said first electric field is less than a peak magnitude of said second electric field.

15. The method of claim **14** wherein passing the charged particles through a first electric field from a source of the charged particles toward an intermediate electrode and then passing the charged particles through a second electric field from said intermediate electrode toward a second electrode comprises passing the charged particles through said first electric field and then through said second electric field when said intermediate electrode has a time-varying voltage applied thereto such that the magnitude of said first electric field is time-varying.

16. The method of claim **14** wherein passing the charged particles through a first electric field from a source of the charged particles toward an intermediate electrode and then passing the charged particles through a second electric field from said intermediate electrode toward a second electrode comprises passing the charged particles through said first electric field and then through said second electric field when said intermediate electrode has a DC voltage applied thereto such that the magnitude of said first electric field is substantially non-varying in time.

17. (canceled)

18. The method of claim **14** wherein passing the charged particles through a first electric field from a source of the charged particles toward an intermediate electrode and then passing the charged particles through a second electric field from said intermediate electrode toward a second electrode comprises passing the charged particles through said first electric field and then through said second electric field when said intermediate electrode defines an intermediate aperture for permitting the charged particles to pass through said intermediate electrode.

19-22. (canceled)

23. The method of claim **14** wherein passing the charged particles through a first electric field from a source of the charged particles toward an intermediate electrode and then passing the charged particles through a second electric field from said intermediate electrode toward a second electrode comprises passing the charged particles through said first electric field and then through said second electric field when the magnitude of said first electric field is less than or equal to a minimum magnitude of said second electric field occurring during a phase acceptance time period associated with a phase acceptance of the cyclotron.

24. (canceled)

25. The method of claim **23** wherein passing the charged particles through said first electric field and then through said second electric field when the magnitude of said first electric field is less than or equal to a minimum magnitude of said second electric field occurring during a phase acceptance time period associated with a phase acceptance of the cyclotron comprises passing the charged particles through said first electric field and then through said second electric field when said phase acceptance is in a range of 20 to 50 degrees.

26. The method of claim **23** wherein passing the charged particles through said first electric field and then through said second electric field when the magnitude of said first electric field is less than or equal to a minimum magnitude of said second electric field occurring during a phase acceptance time period associated with a phase acceptance of the cyclotron comprises passing the charged particles through said first electric field and then through said second electric field when said intermediate electrode has a voltage applied thereto such that the waveform of the magnitude of said second electric field during said phase acceptance time period and the waveform of the magnitude of said first electric field during a corresponding time period offset from said phase acceptance time period have substantially equal waveform shapes.

27. A cyclotron comprising:

(a) first electric field means for passing charged particles through a first electric field from a source of the charged particles toward an intermediate electrode when said source and said intermediate electrode are internal to the cyclotron;

(b) second electric field means for passing the charged particles through a second electric field from said intermediate electrode toward a second electrode when said second electrode is internal to the cyclotron;

(c) time-varying field means for applying a time-varying voltage to said second electrode such that said second electric field is time-varying; and

(d) beam focusing means for causing the magnitude of said first electric field to be less than a peak magnitude of said second electric field.

30. The cyclotron of claim **27** wherein said first electric field means causes said first electric field to be time-varying.

28. The cyclotron of claim **27** wherein said beam focusing means causes the magnitude of said first electric fields to be less than or equal to a minimum magnitude of said second electric field occurring during a phase acceptance time period associated with a phase acceptance of the cyclotron.

31. The cyclotron of claim **28** further comprising waveform shaping means for applying a voltage to said intermediate electrode such that the waveform of the magnitude of said second electric field during said phase acceptance time period and the waveform of the magnitude of said first electric field during a corresponding time period offset from said phase acceptance time period have substantially equal waveform shapes.

29. A kit for reducing divergence of a beam of charged particles in a cyclotron, the kit comprising an intermediate electrode dimensioned for installation within the cyclotron between a source of the charged particles and a second electrode of the cyclotron, said source and said second electrode being internal to the cyclotron, and instructions for exposing the charged particles to a first electric field extending between said source and said intermediate electrode prior to exposing the charged particles to a second electric field extending between said intermediate electrode and said second electrode, said second electrode having a time-varying voltage applied thereto such that said second electric field is time-varying, the magnitude of said first electric field being less than a peak magnitude of said second electric field.

32. The kit of claim **29** wherein said intermediate electrode defines an intermediate aperture for permitting the charged particles to pass through said intermediate electrode.

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