

A DEVICE TO MANIPULATE IONS OF SAME OR DIFFERENT POLARITIES

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5 This invention was made with government support under grant DE-AC05-76RL01830 awarded by the United States Department of Energy. The government has certain rights in the invention.

CROSS REFERENCE TO RELATED APPLICATIONS

10 This application claims the benefit of U.S. Application No. 15/260,046, filed September 8, 2016, which is herein incorporated by reference in its entirety.

FIELD

15 The field pertains to ion manipulation devices.

BACKGROUND

 Ion manipulation technology has allowed the discovery of new applications related to material detection and analysis and composition formation, and has fostered the creation of increasingly useful tools and instruments related to, for example, mass spectrometry. However, 20 problems associated with manipulating ions of the same or different polarities have remained.

SUMMARY

 According to one aspect of the disclosed technology, an apparatus includes a first pair of opposing electrode arrangements situated to confine ions between the first pair opposing electrode 25 arrangements in a confinement volume portion of a confinement volume inwardly laterally in a first confinement direction with respect to a longitudinal ion propagation direction, each opposing electrode arrangement of the first pair including an arrangement of RF electrodes situated to receive an unbiased RF voltage having an alternate phase between adjacent RF electrodes of the arrangement of RF electrodes of the opposing electrode arrangement of the first pair so as to 30 provide the confining of ions between the first pair of opposing electrode arrangements, and a second pair of opposing electrode arrangements separate from the first pair of opposing electrode arrangements and situated to confine the ions between the second pair of opposing electrode arrangements in the confinement volume inwardly laterally in a second confinement direction that complements the first confinement direction, each opposing electrode arrangement of the second

pair including an arrangement of RF electrodes situated to receive an unbiased RF voltage having an alternate phase between adjacent RF electrodes of the arrangement of RF electrodes of the opposing electrode arrangement of the second pair.

In some representative embodiments of the disclosed technology, RF electrodes of each arrangement of RF electrodes of the second pair of opposing electrode arrangements are stacked laterally with respect to the second confinement direction and wherein the RF electrodes of the second pair of opposing electrode arrangements extend longitudinally along the confinement volume and provide confinement of the ions in the second confinement direction. In additional representative embodiments of the disclosed technology, each opposing electrode arrangement of the second pair includes a traveling wave electrode arrangement situated to confine the ions in the confinement volume in the second confinement direction.

According to another aspect of the disclosed technology, a method includes receiving ions in a confinement volume for movement along a longitudinal ion propagation direction, and with a first opposing arrangement of electrodes providing an unbiased RF field, confining the ions in the confinement volume in a first lateral inward direction between the first opposing arrangement of electrodes, and with a second opposing arrangement of electrodes that includes RF electrodes situated to provide an unbiased RF field, confining the ions in the confinement volume in a second lateral inward direction that complements the first inward direction.

In some representative method embodiments of the disclosed technology, the confining of the ions in the second inward direction includes providing an unbiased RF voltage to a pair of opposing arrangements of RF electrodes of the second opposing arrangement of electrodes so as to provide the unbiased RF field, each opposing arrangement forming a stack with adjacent RF electrodes of the stack having an alternate phase, each RF electrode extending longitudinally along the confinement volume so as to provide the confining of the ions in the second inward direction.

In further representative method embodiments of the disclosed technology, the confining of the ions in the second inward direction includes providing an unbiased RF voltage to RF electrodes of a pair of opposing arrangements of electrodes of the second opposing arrangement of electrodes so as to provide the unbiased RF field and ion confinement in the first inward direction in an extended confinement region of the confinement volume and includes providing a variable DC voltage to traveling wave electrodes of the pair of opposing arrangements of electrodes that are alternately arranged between the RF electrodes of the pair of opposing arrangements of electrodes so as to produce a corresponding traveling wave to confine the ions in the extended confinement region in the second inward direction.

According to a further aspect of the disclosed technology, an apparatus includes a first pair of opposing electrode arrangements situated to confine ions between the first pair opposing electrode arrangements in a confinement volume portion of a confinement volume inwardly in a first confinement direction that is perpendicular to an ion propagation direction, each opposing electrode arrangement of the first pair including an arrangement of RF electrodes situated to receive an unbiased RF voltage having an alternate phase between adjacent RF electrodes of the arrangement of RF electrodes of the opposing electrode arrangement of the first pair so as to provide the confining of ions between first pair of opposing electrode arrangements, a second pair of opposing electrode arrangements separate from the first pair of opposing electrode arrangements and situated to confine the ions between the second pair of opposing electrode arrangements in the confinement volume inwardly in a second confinement direction that is mutually perpendicular to the first confinement direction and the ion propagation direction, each opposing electrode arrangement of the second pair including an arrangement of RF electrodes situated to receive an unbiased RF voltage having an alternate phase between adjacent RF electrodes of the arrangement of RF electrodes of the opposing electrode arrangement of the second pair, and a traveling wave electrode arrangement situated between adjacent RF electrodes of the first pair of opposing electrode arrangements and that includes a plurality of traveling wave electrodes extending in a sequence parallel to the ion propagation direction so as to receive a variable DC voltage and to produce a corresponding traveling wave to move the ions along the ion propagation direction, wherein the first and second pairs of opposing electrode arrangements are situated so as to confine ions of opposite polarities.

The foregoing and other objects, features, and advantages of the disclosed technology will become more apparent from the following detailed description, which proceeds with reference to the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is an isometric perspective view of an example ion manipulation apparatus.

FIG. 1B is an end view of the ion manipulation apparatus of FIG. 1A.

FIG. 2A is a top view of an example ion manipulation apparatus manipulating ions of different polarities.

FIG. 2B is an end view of the ion manipulation apparatus example of FIG. 2A.

FIG. 3A is a top cross-sectional view of another example ion manipulation apparatus manipulating ions of different polarities.

FIG. 3B is an end view of the ion manipulation apparatus example of FIG. 3A.

FIG. 4 is an example of another ion manipulation apparatus having a non-rectangular cross-section.

FIG. 5 is an example of another ion manipulation apparatus having multiple ion conduits.

FIG. 6A is an isometric perspective view of another example ion manipulation apparatus.

5 FIG. 6B is a top view of the ion manipulation apparatus example of FIG. 6A.

FIG. 6C is an end view of the ion manipulation apparatus example of FIG. 6A.

FIG. 7 is a top cross-sectional view of another example ion manipulation apparatus manipulating ions of different polarities.

FIGS. 8-10 are end views of additional examples of an ion manipulation apparatus.

10 FIG. 11 is an end view of another example ion manipulation apparatus.

FIG. 12 is a top view of another example ion manipulation apparatus.

FIG. 13 is a top view of another example ion manipulation apparatus.

FIG. 14 is a flowchart of an example method in accordance with the disclosed technology.

15 DETAILED DESCRIPTION

As used in this application and in the claims, the singular forms “a,” “an,” and “the” include the plural forms unless the context clearly dictates otherwise. Additionally, the term “includes” means “comprises.” Further, the term “coupled” does not exclude the presence of intermediate elements between the coupled items.

20 The systems, apparatus, and methods described herein should not be construed as limiting in any way. Instead, the present disclosure is directed toward all novel and non-obvious features and aspects of the various disclosed embodiments, alone and in various combinations and sub-combinations with one another. The disclosed systems, methods, and apparatus are not limited to any specific aspect or feature or combinations thereof, nor do the disclosed systems, methods, and
25 apparatus require that any one or more specific advantages be present or problems be solved. Any theories of operation are to facilitate explanation, but the disclosed systems, methods, and apparatus are not limited to such theories of operation.

Although the operations of some of the disclosed methods are described in a particular, sequential order for convenient presentation, it should be understood that this manner of description
30 encompasses rearrangement, unless a particular ordering is required by specific language set forth below. For example, operations described sequentially may in some cases be rearranged or performed concurrently. Moreover, for the sake of simplicity, the attached figures may not show the various ways in which the disclosed systems, methods, and apparatus can be used in conjunction with other systems, methods, and apparatus. Additionally, the description sometimes

uses terms like “produce” and “provide” to describe the disclosed methods. These terms are high-level abstractions of the actual operations that are performed. The actual operations that correspond to these terms will vary depending on the particular implementation and are readily discernible by one of ordinary skill in the art. In some examples, values, procedures, or apparatus’ are referred to as “lowest”, “best”, “minimum,” or the like. It will be appreciated that such descriptions are intended to indicate that a selection among many used functional alternatives can be made, and such selections need not be better, smaller, or otherwise preferable to other selections.

Some examples are described in relation to one more longitudinal and lateral directions generalized to correspond to ion movement or confinement. Directions typically apply to ion movement, trapping, and confinement and are provided by electric fields produced by one or more electrodes that are arranged to define one or more volumes of various shapes, sizes, and configurations. A direction can correspond to a single path, multiple paths, bi-directional movement, inward movement, outward movement, or a range of movements. Actual ion movement paths vary and can depend on the various characteristics of the electrode arrangements and electric fields produced by the corresponding electrodes and the positional, polarity, kinetic, or other characteristics of the ions received in a confinement volume. Directions referred to herein are generalized and actual specific particle movements typically correspond to electric fields produced and the electrical mobilities of the ions propagating in relation to the electric fields.

The disclosed technology is directed to devices, apparatus, and methods of manipulating ions, including the use of electric fields to create field-defined pathways, traps, conduits, and switches to manipulate ions with minimal or no losses. In some embodiments, complex sequences of ion separations, transfers, path switching, and trapping can occur in the volume provided between electrode arrays situated on one or more surfaces positioned apart from each other. In some examples, ion confining fields are provided by unbiased radio frequency (RF) electric fields. In additional examples, ion confining fields provided by unbiased RF fields and traveling wave electric fields. In representative examples, ions of opposite polarity are moved, trapped, or manipulated using RF electric fields or RF and traveling wave electric fields. RF electric fields are typically applied so that RF fields generated by adjacent RF electrodes are out of phase, typically by approximately 180°, to form an alternating RF field arrangement that inhibits the ions from approaching the electrodes and that provides confinement. Confinement can be provided over a range of pressures (e.g., less than approximately 0.001 torr to approximately 1000 torr), and over a useful, broad, and adjustable mass to charge (m/z) range associated with the ions. In some examples ions are manipulated for analysis through mass spectrometry or with a mass spectrometer, and where pressures of less than approximately 0.1 torr to approximately 50 torr can

be used to readily manipulate ions over a useful m/z range, e.g., m/z 20 to greater than approximately 5,000. In some examples, ion confinement volumes includes gases or reactants. Arrangements of RF electrodes and traveling wave electrodes receive corresponding potentials that allow creation of ion traps and/or conduits in the volume or gap between the electrode
5 arrangements so that lossless or substantially lossless storage and/or movement of ions of the same or different polarities can be achieved, including without the application of static or superimposed DC potentials. For example, lossless manipulation can include losses of less than 0.1%, 1%, or 5% of ions injected into a corresponding ion confinement volume.

Traveling waves are typically created by dynamically applying DC potentials to a plurality
10 of electrodes arranged in one or more sequences. Traveling wave electrode sets can be formed by one or more sequences of traveling wave electrodes situated in series. As the DC potentials are varied between adjacent electrodes of a traveling wave electrode sequence, a traveling wave can be formed with a speed based on the time dependent variation of the DC potentials. Varying traveling wave characteristics can affect and manipulate various movements of ions having different ion
15 mobilities, including producing ion confinement, lossless transport, and ion separation. In some examples, in conjunction with traveling waves, ions can be losslessly confined in an ion confinement volume for extended durations, such as multiple hours. One such characteristic is the traveling wave speed, with ions that have higher mobility moving or surfing with the traveling wave and ions that have lower mobility rolling over and lagging behind the traveling wave to allow
20 ion separation. Another such characteristic is traveling wave amplitude, which can transport ions with lower ion mobilities with a corresponding increase in traveling wave amplitude. Traveling wave amplitudes are typically selected based on ion mobility characteristics and the desired ion manipulation to be in the range of greater than 0 V up to 30 V, 50 V, 80 V, 100 V, or greater. Traveling wave speeds are typically selected based on ion mobility characteristics and the desired
25 ion manipulation to be in the range of less than 5 m/s, 20 m/s 50 m/s, 100 m/s, 200 m/s, or 500 m/s. Traveling wave frequencies are typically selected between 10 kHz and 200 kHz.

FIGS. 1A-1B show an example of an ion manipulation apparatus 100 situated to receive ions 102 through an entrance aperture 104 in an ion confinement volume 106 and to propagate, separate, trap, and/or move the ions 102, including transporting the ions 102 from the entrance
30 aperture 104 to an exit aperture 105. The ion confinement volume 106 is generally defined between a first pair of opposing electrode arrangements 108a, 108b and a second pair of opposing electrode arrangements 110a, 110b. An ion propagation axis 112 extends along the ion confinement volume 106 and indicates a general longitudinal propagation direction for the ions 102. In some examples, the ions 102 have opposite polarities and are moved through the ion

confinement volume 106 from the entrance aperture 104 to the exit aperture 105. In representative examples, the opposing electrode arrangements 108a, 108b have a mirrored configuration and the opposing electrode arrangements 110a, 110b have a mirrored configuration, forming a symmetric confinement area perpendicular to the ion propagation axis through the ion confinement volume. In further examples, electrode arrangements or portions of electrode arrangements are not identical or are not mirrored.

In representative examples, each of the opposing electrode arrangements 108a, 108b includes an arrangement of electrodes 114 that extend along the length of the ion confinement volume 106 and that are situated to receive one or more RF voltages, typically in the frequency range of 100 kHz to 100 MHz, which are not biased with a DC voltage, so as to provide confinement of ions with the same or different polarities. The electrodes 114 are arranged so as to receive RF voltages alternately so that the RF voltages received by adjacent electrodes of the electrodes 114 are approximately 180° out of phase from each other. With the applied RF voltages, the electrodes 114 move and confine the ions 102 in the ion confinement volume 106 laterally in an inward direction 115 between the opposing electrode arrangements 108a, 108b, which is generally perpendicular or normal to the ion propagation axis 112 or longitudinal path through the ion confinement volume 106 in the parallel configuration of opposed electrode arrangements 108 shown. The RF voltages received by the electrodes 114 can vary, e.g., with respect to frequency and amplitude, over time or between adjacent electrodes 114.

Each of the opposing electrode arrangements 108a, 108b also includes one or more traveling wave electrode arrangements 116 situated between adjacent electrodes 114. In some examples, traveling wave electrode arrangements 116 are alternately situated between adjacent electrodes 114. In further examples, two or more traveling wave electrode arrangements 116 are situated between adjacent electrodes 114, and in additional examples, two or more electrodes 114 are situated between adjacent traveling wave electrode arrangements 116. The traveling wave electrode arrangements 116 can each include a sequence of electrodes 117 such as a plurality of electrode segments extending along the length or a portion of the length of the ion confinement volume 106 and that are situated to receive separate time-varying DC voltages. The DC voltages vary with time so as to produce a traveling wave along the selected traveling wave electrode arrangement 116. The traveling wave produces a movement, net movement, separation, or trapping of the ions 102 in the ion confinement volume 106 associated with the direction of the traveling wave, such as in the direction of the ion propagation axis 112 or longitudinal extent of the ion confinement volume 106. In some examples, traveling wave characteristics such as wave speed or amplitude are varied between different traveling wave electrode arrangements 116.

In representative examples, each of the opposing electrode arrangements 110a, 110b includes a plurality of electrodes 118 each extending parallel to each other along the length of the ion confinement volume 106 and spaced apart from each other in a direction parallel to the inward direction 115 so as to form an electrode stack. Each plurality of electrodes 118 is situated to receive RF voltages, such as in the range of 100 kHz to 100 MHz, which are not biased with a DC voltage, so as to provide confinement of ions with the same or different polarities. Each plurality of electrodes 118 receives RF voltages alternately so that the RF voltages received by adjacent electrodes of the plurality of electrodes 118 are approximately 180° out of phase with each other. The RF voltages received by the electrodes 118 need not be identical, and in many examples are not identical, to those received by the electrodes 114 and can also vary, e.g., with respect to frequency and amplitude, over time or between adjacent electrodes 118. With the applied RF voltages, the electrodes 118 move and confine the ions 102 in the ion confinement volume 106 laterally in an inward direction 119 that complements or supports the inward direction 115. In representative examples, the inward direction 119 is generally perpendicular to the ion propagation axis 112 and the inward direction 115. The electrodes 118 can have a width that extends laterally (e.g., parallel to the inward direction 119) so that the electrodes 118 are substantially planar. In some embodiments, the ion propagation axis 112 is curved or bent. In further examples, the lateral inward directions 115, 119 are not perpendicular to each other or to the ion propagation axis 112. RF fields generated with the electrodes 118 have sufficient field penetration so as to provide suitable ion confinement.

FIGS. 2A-2B depicts a representative example of an ion manipulation apparatus 200 manipulating ions 202 into three ion sets 204a-204c that are confined within a confinement volume 206. The confinement volume 206 is defined between a first pair of opposing electrode arrangements 208a, 208b that includes RF electrodes 210 that provide RF electric fields extending into the confinement volume 206 which are phase shifted between adjacent RF electrodes 210 (e.g., by 180°). The first pair of opposing electrode arrangements 208a, 208b also includes a plurality of traveling wave electrode sets 212 that includes traveling wave electrodes 213 that are situated to move, separate, or trap the ions 202 along an ion propagation direction 214, which is generally towards the top or bottom, or both, of FIG. 2A. For example, the ions 202 can be inserted into the ion confinement volume through an open end and become segregated or spread laterally and/or longitudinally into a plurality of ion groups within the confinement volume 206.

The confinement volume 206 is further defined between a second pair of opposing electrode arrangements 216a, 216b. The opposing electrode arrangements 216a, 216b form respective electrode stacks having a plurality of RF electrodes 218 spaced apart from each other in a first

direction that extends vertically as depicted in FIG. 2B and that is generally perpendicular to the ion propagation direction 214. The RF electrodes 218 generate electric fields that extend into the confinement volume 206 and that are also phase-shifted between adjacent RF electrodes 218 so as to support or provide a lateral confinement of ions in the confinement volume 206 at least in a second direction away from the RF electrodes 218 and into the confinement volume 206. The confinement provided by the RF electrodes 218 generally complements a lateral confinement provided by the RF electrodes 210, so as to support inhibiting the escape of the ions 202 from the confinement volume 206 or the contact of the ions 202 with the RF electrodes 218 and corresponding surfaces. In representative examples, the second direction is generally perpendicular to the first direction in which the RF electrodes 218 of the stacks are spaced apart and perpendicular to the ion propagation direction 214.

An asymmetric traveling wave voltage between 0 V and 20 V is applied to the traveling wave electrode sets 212 that corresponds to an amplitude of the traveling wave. A traveling wave speed of 100 m/s is produced by varying the traveling wave voltage between adjacent traveling wave electrodes 213 in the traveling wave electrode sets 212. The duration of the traveling wave can vary so that one or more adjacent traveling wave electrodes 213 can have the same or different voltage. The ion sets 204a-204c each have an m/z of 622 though the ions 202 of the ion sets 204a, 204c have a positive polarity and the ions 202 of the ion set 204b have a negative polarity. An RF voltage of 150 V is applied to the RF electrodes 210, 218 so as to confine the ions 202 of the ion sets 204a-204c within the confinement volume 206. The negatively charged ions 204b are generally confined to a center region of the confinement volume 206 and the positively charged ions 204a, 204c are generally confined to side regions adjacent to the center region. In some examples, the side regions can overlap the center region so that ions of different polarities can become separated and remain overlapping within the confinement volume 206 and in other examples the side regions can be separate from center region so that ions of different polarities are separated and non-overlapping within the confinement volume 206.

FIGS. 3A and 3B shows an ion manipulation apparatus 300 having a substantially similar electrode arrangement as the ion manipulation apparatus 200. A pair of opposite electrode arrangements 302a, 302b include RF electrodes 304 extending along a propagation direction 306 for the confinement of ions 308 propagating in a confinement volume 310 of the ion manipulation apparatus 300, and further include traveling wave electrodes 312 forming traveling wave electrode sets 314 that also extend along the propagation direction 306. Another pair of opposite electrode arrangements 316a, 316b includes RF electrodes 318 that also extend along the propagation direction 306. The RF electrodes 304, 318 provide RF electric fields that extend into the

confinement volume 310 so as to laterally confine the ions 308 within the confinement volume 310 and provide lossless manipulation of the ions 308. The propagation direction 306 is shown to correspond with an axis centrally situated in the confinement volume 310 though it will be appreciated that ions 308 are not confined to the axis itself. As shown, the ions 308 have an m/z equal to 622 and include three separate ion sets 320a-320c with the ion sets 320a, 320c having a negative polarity and the ion set 320b having a positive polarity. A symmetric traveling wave voltage varying between -10 V and 10 V is applied to the traveling wave electrodes 312 of the traveling wave electrode sets 314 to move the ions 308 in the confinement volume 310. The negatively charged ion set 320a and the positively charged ion set 320b are generally confined to symmetrically situated adjacent side regions and the ions 308 of the negatively charged ion set 320c propagate in a side region opposite the ion set 320a. Varying a traveling wave voltage from symmetrical to non-symmetrical (for example) can produce different separations between ions of opposite polarities propagating within a common confinement volume.

In FIG. 4, an end view of an example of an ion manipulation apparatus 400 is shown. The ion manipulation apparatus 400 includes an opposing pair of electrode arrangements 402a, 402b each including a plurality of RF electrodes 404 and a plurality of traveling wave electrodes arrangements 406 interposed between adjacent RF electrodes of the plurality of RF electrodes 404. The ion manipulation apparatus 400 also includes another opposing pair of electrode arrangements 408a, 408b situated adjacent to the pair of electrode arrangements 402 and each including a plurality of adjacently situated and spaced apart RF electrodes 410. The opposing pairs of electrode arrangements 402, 408 are situated so as to define an ion confinement area 412. An ion confinement volume is formed as the electrodes 404, 410 also generally extend into the plane of FIG. 4. The ion confinement area 412 can have various shapes, including rectangular and non-rectangular shapes, between different examples of the ion manipulation apparatus 400 or within the same apparatus 400. For example, different RF electrodes 410 can extend into the confinement area by different amounts. In some examples, the extent of the RF electrodes 410 into the ion confinement area 412 varies along the length so that a tapered, expanding, curved, merging, or other shape is formed for the ion confinement volume.

FIG. 5 shows an end view of an example ion manipulation apparatus 500 that includes two ion confinement areas 502, 504 defining separate ion conduits. A first pair of opposing electrode arrangements 506a, 506b and a second pair of opposing electrode arrangements 508a, 508b surround and define the ion confinement area 502. A third pair of opposing electrode arrangements 510a, 510b and a fourth pair of opposing electrode arrangements 512a, 512b surround and define the ion confinement area 504. In representative examples, a portion or all of electrodes of the

electrode arrangements 508b, 512a are the same so that the ion confinement areas 502, 504 share a common electrode border. The electrodes of the pairs of opposing electrode arrangements 506, 510 include RF electrodes 514 extending into the plane of FIG. 5 along the direction of propagation of confined ions. Adjacent RF electrodes 514 typically have an out-of-phase relationship, for example, by approximately 180°. Traveling wave electrodes 516 are situated between adjacent RF electrodes 514 and provide movement and confinement of the ions propagating in the ion conduits. The electrodes of the pairs of opposing electrode arrangements 508, 512 include RF electrodes 518 which also typically have an out-of-phase relationship between adjacent RF electrodes 518. In some examples, adjacent ion conduits can be arranged so that other sides of ion confinement areas share a common electrode border. For example, the electrodes of the electrode arrangements 506a, 510b can be the same so as to form a common border and position the ion confinement area 504 adjacent the ion confinement area 502 in the plane of FIG. 5.

FIGS. 6A-6C show another example of an ion manipulation apparatus 600 situated to confine ions in a confinement volume 602. A first pair of opposing electrode sets 604a, 604b is arranged so as to define two opposing boundaries 605a, 605b of the confinement volume 602. Each of the electrode sets 604a, 604b includes a plurality of traveling wave electrode sets 606 and RF electrodes 608 that extend between opposing ends 610, 612 of the confinement volume 602. The RF electrodes 608 provide ion confinement between the first pair of electrode sets 604, e.g., in a first lateral confinement direction that is generally perpendicular to a longitudinal ion movement direction between the opposing ends 610, 612. The traveling wave electrode sets 606 provide a DC traveling wave voltage between traveling wave electrodes 614 in each traveling wave electrode set 606 so as to produce a traveling wave electric field that provides the ion movement in the confinement volume 602 between the opposing ends 610, 612, e.g, from the end 610 to the end 612, from the end 612 to the end 610, from one of the ends 610, 612 to become trapped in the confinement volume 602, from one of the ends 610, 612 to become separated into different ion groupings within the confinement volume 602, etc.

A second pair of opposing electrode sets 616a, 616b is arranged to provide confinement of the ions in the confinement volume 602 between two opposing boundaries 617a, 617b in a second lateral confinement direction that complements the first lateral confinement direction. In some examples, the second confinement direction can be mutually perpendicular to the first confinement and ion movement directions. In further examples, additional lateral confinement directions complement the first and second lateral confinement directions. The electrode set 616a includes a pair of opposing electrode arrangements 618a, 618b spaced apart across a confinement volume portion 620 adjacent to a center confinement volume portion 622. Each of the opposing electrode

arrangements 618a, 618b includes a plurality of RF electrodes 624 and a plurality of traveling wave electrodes 626 extending between the opposing ends 610, 612. The RF electrodes 624 move ions in the confinement volume portion 620 away from the opposing electrode arrangements 618 and the traveling wave electrodes 626 are situated to move or confine the ions in the second lateral ion confinement direction away from the confinement volume boundary 617a and towards the center confinement volume portion 622.

The electrode set 616b includes a similar pair of opposing electrode arrangements 628a, 628b spaced apart across a confinement volume portion 630 adjacent to the center confinement volume portion 622, with each including a plurality of RF electrodes 632 and a plurality of traveling wave electrodes 634. The RF electrodes 632 move ions in the confinement volume portion 622 away from the opposing electrode arrangements 628 and the traveling wave electrodes 634 are situated to move the ions in the second lateral ion confinement direction, away from the confinement volume boundary 617b and towards the center confinement volume portion 622. In representative examples, the opposing electrode arrangements 616a, 616b extend adjacently from the opposing electrode arrangements 604a, 604b so that the electrodes of the electrode arrangements 604a, 618a, 628a can be associated with a first common surface and the electrodes of the electrode arrangements 604b, 618b, 628b can be associated with a second common surface spaced apart from the first common surface. For example, the first and second common surfaces can be printed circuit boards with electrode arrangements formed on the respective surfaces. In some examples, the traveling wave characteristics, including peak-to-peak voltage, wave speed, duration, etc., are the same for the traveling wave electrodes 626 and the traveling wave electrode sets 606. In additional examples, the traveling wave characteristics can be different, including between the traveling wave electrodes 626, 634. The RF field characteristics associated with the electrodes 608 can be same or different from the RF field characteristics produced by the RF electrodes 624, 632.

FIG. 7 shows a top view of an example ion manipulation apparatus 700 that includes a first set of ions (black) 702 having a positive polarity and a second set of ions (dark grey) 703 having a negative polarity as the first set of ions 702, both confined in a confinement volume 704. The confinement volume 704 is defined between a first set of electrodes 706 and a second set of electrodes opposed and spaced apart from the first set of electrodes 706 and which is omitted to show the confined first and second sets of ions 702, 703 in the confinement volume 704. In typical examples the second set of electrodes is a substantial mirror copy of the first set of electrodes 706.

The first set of electrodes 706 includes a plurality of traveling wave electrode sets 708 each including a plurality of traveling wave electrodes 710 extending in a sequence. The traveling wave

electrodes 710 are situated to receive separate variable DC voltages corresponding to a traveling wave electric field that travels along the sequence of traveling wave electrodes 710 with predetermined traveling wave characteristics, such as traveling wave speed, amplitude, frequency, crest duration, etc. The traveling wave characteristics associated with the traveling wave electrode sets 708 typically correspond with separation, trapping, or movement of the first and second sets of ions 702, 703 along the direction of the sequences of traveling wave electrodes 710. A plurality of RF electrodes 712 are interposed between the traveling wave electrode sets 708 and inhibit the first and second sets of ions 702, 703 from impinging on the first set of electrodes 706 or otherwise escaping the confinement volume 704 (e.g., between the RF electrodes 712 and traveling wave electrodes 710).

The first set of electrodes 706 further includes a pair of opposing traveling wave electrode sets 714a, 714b, each including a plurality of traveling wave electrodes 716 that extend along the ion manipulation apparatus 700 similar to the traveling wave electrode sets 708 and RF electrodes 712. The opposing traveling wave electrode sets 714a, 714b are situated to receive separate variable DC voltages that correspond to a traveling wave electric field that travels in a different direction with respect to the general movement direction of the first and second sets of ions 702, 703 being directed along the length of the traveling wave electrode sets 708, such as perpendicularly. The first set of electrodes 706 further includes a plurality of RF electrodes 716 that inhibit propagation of the first and second sets of ions 702, 703 to the RF electrodes 716 and the opposing traveling wave electrode sets 714a, 714b. The characteristics of the traveling waves formed by the traveling wave electrode sets 714a, 714b are selected so as to provide lateral confinement, or guarding, of the first and second sets of ions 702, 703 inside the confinement volume 704 that complements the confinement provided by the RF electrodes 712.

In the example shown, the first and second sets of ions 702, 703 extend into lateral regions 716a, 716b of the confinement volume 704. The RF electrodes 716 inhibit ion travel to the RF electrodes 716 and traveling wave electrodes sets 714a, 714b in the corresponding lateral regions 716a, 716b. The traveling wave characteristics corresponding to the traveling wave electrode sets 708 that move the first and second sets of ions 702, 703 along an ion propagation path include a traveling wave speed of 100 m/s and a symmetric amplitude of ± 15 V. The traveling wave characteristics corresponding to the opposing traveling wave electrode sets 714a, 714b that provide a confinement of the first and second sets of ions 702, 703 within the confinement volume 704 include a traveling wave speed of 30 m/s and a symmetric amplitude of ± 20 V.

FIG. 8 shows an input end of an example ion manipulation apparatus 800 that includes a pair of opposing electrode arrangements 802, 804 situated on respective interior surfaces 806, 808

of housing members 810, 812. Electrodes or electrode sets of the opposing electrode arrangements 802, 804 extend into the plane of FIG. 8 and are situated to confine ions propagating in an ion confinement volume 814 defined between the opposing electrode arrangements 802, 804. Each of the opposing electrode arrangements 802, 804 includes a plurality of traveling wave electrode sets 816 situated to move the ions in the ion confinement volume 814 into the plane of FIG. 8 and a pair of opposing traveling wave electrode sets 818a, 818b situated to confine the ions in the ion confinement volume 814 through movement in an inward lateral direction, indicated generally by arrows 820. Each of the opposing electrode arrangements 802, 804 also includes a plurality of RF electrodes 822 that confine ions in an inward lateral direction away from the interior surfaces 806, 808. As shown, the inward lateral direction of confinement provided by the RF electrodes is generally perpendicular to the inward lateral direction indicated by the arrows 820, though it will be appreciated that the confinement directions can vary based on the shape of the electrode arrangements, corresponding electric field strengths, ion characteristics (e.g., mobility, polarity, m/z, etc.), confinement volume shape, etc.

FIG. 9 depicts another example ion manipulation apparatus 900 viewed on-end. The ion manipulation apparatus 900 includes a pair of opposing electrode arrangements 902, 904 each including a plurality of wire electrodes 906 shown, for example, with a circular cross-section. The wire electrodes 906 can include RF electrodes situated to provide confinement of ions propagating in an interior ion confinement volume 908 defined between the opposing electrode arrangements 902, 904 and a plurality of sets of traveling wave electrodes situated to provide confinement of ions propagating in the ion confinement volume 908 or movement of ions in the ion confinement volume 908. FIG. 10 depicts another example ion manipulation apparatus 1000 viewed on-end. A first pair of opposing electrode arrangements 1002, 1004 includes a plurality of traveling wire electrode sets 1006 each including a plurality of wire electrodes and situated across an ion confinement volume 1008. The first pair of opposing electrode arrangements 1002, 1004 further includes a plurality of RF wire electrodes 1010 alternately situated between adjacent traveling electrode sets 1006 and so as to provide confinement of ions between the first pair of opposing electrode arrangements 1002, 1004. A second pair of opposing electrode arrangements 1012, 1014 includes a plurality of adjacent RF wire electrodes 1016 situated to provide ion confinement in the ion confinement volume 1008 between the second pair of opposing electrode arrangements 1012, 1014.

In FIG. 11, an example ion manipulation apparatus 1100 is shown which includes a pair of opposing curved electrode arrangements 1102, 1104 extending into the plane of FIG. 11 and spaced apart across a confinement volume 1106. In some examples, the opposing curved electrode

arrangements 1102, 1104 include a plurality of traveling wave electrode sets 1108 situated to receive a traveling wave voltages and to move ions confined in the confinement volume 1106 into or out of the plane of FIG. 11. RF electrodes 1110 with an adjacently alternating phase are typically interposed between adjacent traveling wave electrode sets 1108 in order to inhibit ions in the confinement volume 1106 from contacting or reaching the proximity of the RF electrodes 1110 and traveling wave electrode sets 1108 and to confine the ions in the confinement volume 1106.

Each of the opposing curved electrode arrangements 1102, 1104 includes an opposing pair of electrode arrangements 1112, 1114 situated adjacent to the traveling wave electrode sets 1108 and RF electrodes 1110. In some embodiments, the opposing pair of electrode arrangements 1112, 1114 includes a pair of opposing traveling wave electrode sets 1116 situated to direct ions inward into the confinement volume 1106 between the traveling wave electrode sets 1108, so as to complement the confinement provided by the RF electrodes 1110. The opposing pair of electrode arrangements 1112, 1114 also includes a plurality of RF electrodes 1118, which can be similar or the same as the RF electrodes 1110, alternately situated between the traveling wave electrodes of the opposing traveling wave electrode sets 1116. In additional embodiments, the opposing pair of electrode arrangements 1112, 1114 includes a plurality of RF electrodes 1118 in the place of the traveling wave electrodes of the traveling wave electrode sets 1116. In further embodiments, end stacks 1120 of RF electrodes can be situated to further inhibit ions from escaping the confinement volume 1106. In typical examples, adjacent RF electrodes are 180° out of phase.

In FIG. 12, an example of an ion manipulation apparatus 1200 includes a first tapered electrode arrangement 1202 opposing a second tapered electrode arrangement, which is omitted for clarity in the top view of the apparatus 1200 that is shown. An ion confinement volume, in which ions are separated, trapped, or moved, is defined between the first tapered electrode arrangement 1202 and the second tapered electrode arrangement. In typical examples, the second tapered electrode arrangement substantially mirrors the configuration of the first tapered electrode configuration 1202. The tapered electrode arrangement 1202 includes a plurality of traveling wave electrode arrangements 1204 having sequences of traveling wave electrodes 1206 that taper along the length of the sequences and that produce ion movement in the ion confinement volume in a direction corresponding to the length direction of the electrode sequences. The tapered electrode arrangement 1202 further includes a pair of opposing traveling wave electrode arrangements 1208a, 1208b having respective sequences of traveling wave electrodes 1210 producing ion movement in a general interior direction, e.g., from left to right in FIG. 12 for traveling wave electrode arrangement 1208a and from right to left for traveling wave electrode arrangement 1208b. A

plurality of interposed RF electrodes 1212 are situated to inhibit ions from contacting the first tapered electrode arrangement 1202 and the second tapered electrode arrangement.

FIG. 13 depicts an example ion manipulation apparatus 1300 that includes a first curved electrode arrangement 1302 and a second curved electrode arrangement (not shown) opposing and spaced apart from the first curved electrode arrangement 1302 to form an ion confinement volume extending along a curved axis 1303. A plurality of curved traveling wave electrode sequences 1304 include traveling wave electrodes 1306 situated to receive a DC traveling wave voltage to produce a movement of the ions along the curved shape of the ion confinement volume. In some examples, the traveling wave electrodes 1306 can be linear segments forming a piece-wise curved shape. A plurality of RF electrodes 1308 are situated between adjacent traveling wave electrode sequences 1304. In some examples, an opposing pair of traveling wave electrodes sets 1310a, 1310b are situated to direct ions in an inward lateral direction, e.g., generally normal or perpendicular to a tangent of the curved axis 1303, so as to provide confinement, separation, or trapping of ions within the ion confinement volume. A plurality of RF electrodes 1312 are situated between the electrodes of the traveling wave electrode sets 1310a, 1310b and are situated to receive an RF voltage so as to inhibit contact of ions with the RF electrodes 1312, the electrode sets 1310a, 1310b, or corresponding surfaces on which the RF electrodes 1312 and electrode sets 1310a, 1310b may be mounted, formed, or otherwise situated. In some examples, end stacks of RF electrodes 1312 can extend into or out of the plane from edge electrodes 1313a, 1313b so as to provide additional confinement of ions within the ion confinement volume in the inward lateral direction, e.g., generally perpendicular to the curved axis 1303. In further examples with end stacks of RF electrodes 1312 the traveling wave electrode sets 1310a, 1310b can be omitted.

In FIG. 14, a flowchart shows an example method 1400 for manipulating ions, including ions of the same or different ion polarities. In a method act 1402, ions are received in a confinement volume to move the ions, including through transport, separation, trapping, etc., in relation to a longitudinal ion propagation direction. In a method act 1404, with a first opposing arrangement of electrodes providing an unbiased RF field, ions are confined in the confinement volume in a first lateral inward direction between the first opposing arrangements of electrodes. In some examples, the first inward direction is perpendicular or normal to the ion propagation direction. In a method act 1406, with a second opposing arrangement of electrodes that includes RF electrodes situated to provide an unbiased RF field, ions are confined in a second inward lateral direction that complements the first lateral inward direction. The ions become confined ions between the first and second arrangements of electrodes within the ion confinement volume for lossless propagation of the ions. In particular examples, the second inward direction of

confinement is mutually perpendicular to the ion propagation direction and the first inward direction.

In representative examples, the confining of ions in the second inward direction includes providing an unbiased RF voltage to a pair of opposing arrangements of RF electrodes of the second opposing arrangement of electrodes so as to provide the unbiased RF field, each opposing arrangement forming a stack with adjacent RF electrodes of the stack having an alternate phase, each RF electrode extending along the ion propagation direction so as to provide the confining of the ions in the second inward direction. In other representative examples, the confining of the ions in the second inward direction includes providing an unbiased RF voltage to RF electrodes of a pair of opposing arrangements of electrodes of the second opposing arrangement of electrodes so as to provide the unbiased RF field and ion confinement in the first inward direction in an extended confinement region of the confinement volume and includes providing a variable DC voltage to traveling wave electrodes of the pair of opposing arrangements of electrodes that are alternately arranged between the RF electrodes of the pair of opposing arrangements of electrodes so as to produce a corresponding traveling wave to move the ions in the extended confinement region in the second inward direction.

In view of the many possible embodiments to which the principles of the disclosed technology may be applied, it should be recognized that the illustrated embodiments are only representative examples and should not be taken as limiting the scope of the disclosure.

Alternatives specifically addressed in these sections are merely exemplary and do not constitute all possible alternatives to the embodiments described herein. For instance, various components of systems described herein may be combined in function and use. We therefore claim all that comes within the scope and spirit of the appended claims.

CLAIMS

1. An apparatus, comprising:

a first pair of opposing electrode arrangements configured to confine ions received between the first pair opposing electrode arrangements in a confinement volume portion of a confinement volume inwardly laterally in a first confinement direction with respect to a longitudinal ion propagation direction, each opposing electrode arrangement of the first pair including an arrangement of RF electrodes configured to receive an RF voltage having an alternate phase between adjacent RF electrodes of the arrangement of RF electrodes of the opposing electrode arrangement of the first pair and to confine received ions between the first pair of opposing electrode arrangements; and

a second pair of opposing electrode arrangements separate from the first pair of opposing electrode arrangements and configured to confine ions received between the second pair of opposing electrode arrangements in the confinement volume inwardly laterally in a second confinement direction that complements the first confinement direction, each opposing electrode arrangement of the second pair including an arrangement of RF electrodes configured to receive an RF voltage having an alternate phase between adjacent RF electrodes of the arrangement of RF electrodes of the opposing electrode arrangement of the second pair;

a first traveling wave electrode arrangement situated between adjacent RF electrodes of the first pair of opposing electrode arrangements and that includes a plurality of traveling wave electrodes extending in a longitudinal sequence in the ion propagation direction, in which the traveling wave electrodes are configured to receive a variable DC voltage and to produce a corresponding traveling wave configured to manipulate movement of the ions within the confinement volume.

2. An apparatus according to Claim 1, in which the first and second ion confinement directions are mutually perpendicular to the ion propagation direction.

3. An apparatus according to Claim 1, in which the first and second pairs of opposing electrode arrangements are configured to confine ions of opposite polarities.

4. An apparatus according to Claim 1, in which the first and second pairs of opposing

electrode arrangements are configured to laterally separate, with respect to the ion propagation

direction, received ions of different polarity into non-overlapping ion groups in the confinement volume portion.

5. An apparatus according to Claim 1, in which RF electrodes of each arrangement of RF electrodes of the second pair of opposing electrode arrangements are stacked in the second
5 confinement direction, and in which the RF electrodes of the second pair of opposing electrode arrangements extend longitudinally in the ion propagation direction and provide confinement of received ions in the second confinement direction.

6. An apparatus according to Claim 5, in which each of the stacked RF electrodes includes one or more substantially planar surfaces extending laterally in the second confinement
10 direction.

7. An apparatus according to Claim 5, in which the RF electrodes are wire electrodes.

8. An apparatus according to Claim 5, in which a portion of at least two RF electrodes of the second pair of opposing electrode arrangements extend into the confinement volume portion by different amounts to provide a non-rectangular confinement cross-section of the
15 confinement volume portion .

9. An apparatus according to Claim 1, in which each opposing electrode arrangement of the second pair includes a second traveling wave electrode arrangement configured to confine ions received in the confinement volume in the second confinement direction.

10. An apparatus according to Claim 9, in which each second traveling wave electrode
20 arrangement includes a plurality of traveling wave electrodes extending longitudinally in the ion propagation direction and spaced apart from each other in the second confinement direction, in which the plurality of traveling wave electrodes of the second traveling wave electrode arrangement are configured to receive a variable DC voltage and to produce a corresponding traveling wave to confine ions within the confinement volume in the second
25 confinement direction inward.

11. An apparatus according to Claim 9, in which the second traveling wave electrode arrangements are configured to confine received ions in an extended confinement volume portion of the confinement volume that is laterally adjacent to the confinement volume portion of the first pair of opposing electrode arrangements with respect to the ion propagation
30 direction.

12. An apparatus according to Claim 10, in which the RF electrodes of the second pair of opposing electrode arrangements extend longitudinally in the ion propagation direction and are spaced apart from each other in the second confinement direction.
13. An apparatus according to Claim 12, in which the traveling wave electrodes of the second pair of opposing electrode arrangements are situated between adjacent RF electrodes of the second pair of opposing electrode arrangements.
14. An apparatus according to Claim 11, in which the first and second pairs of opposing electrode arrangements are situated on a pair of opposing surfaces defining an electrodeless gap that includes the confinement volume portion and the extended confinement volume portion.
15. An apparatus according to Claim 1, in which the confinement volume defines a first ion conduit and the apparatus further comprises a second ion conduit separate and laterally spaced apart from the first ion conduit and in which the second ion conduit includes a plurality of electrode arrangements and at least one of the electrode arrangements of the second ion conduit is an opposing electrode arrangement of the first or second pairs of opposing electrode arrangements of the first ion conduit.
16. An apparatus according to Claim 1, in which the alternate phase between adjacent RF electrodes of the arrangement of RF electrodes of the opposing electrode arrangement of each of the first pair and the second pair is 180 degrees out of phase.
17. An apparatus according to Claim 1, in which the confinement volume is curved or tapered.
18. A method, comprising:
- receiving ions in a confinement volume defined between a first pair of opposing electrode arrangements, each of the first pair of opposing electrode arrangements including a first arrangement of RF electrodes and a first arrangement of traveling wave electrodes situated between adjacent RF electrodes of the first arrangement of RF electrodes, in which the first traveling wave electrodes extend in a longitudinal sequence with respect to a longitudinal ion propagation direction;

moving the received ions along the longitudinal ion propagation direction in response to receipt of a variable DC voltage by the traveling wave electrodes of the first traveling wave electrode arrangement;

providing a first RF field in response to receipt of a first RF voltage by the RF electrodes of the first RF electrode arrangement;

confining, by the first RF field, the received ions in the confinement volume in a first lateral inward direction between the first pair of opposing electrode arrangements with respect to the ion longitudinal propagation direction;

providing a second RF field in response to receipt of a second RF voltage by RF electrodes of a second RF electrode arrangement of a second pair of opposing arrangement of electrodes; and

confining, by the second RF field, the ions in the confinement volume in a second lateral inward direction with respect to the ion longitudinal propagation direction that complements the first inward direction.

19. A method according to Claim 18, in which the RF electrodes of each second RF electrode arrangement forms a stack with adjacent RF electrodes of the stack configured to receive the RF voltage having an alternate phase, and in which each RF electrode of each second RF electrode arrangement extends longitudinally along the confinement volume.

20. A method according to Claim 18, in which:

the first pair of opposing electrode arrangements are spaced apart across a center confinement volume portion of the confinement volume;

the second pair of opposing arrangement of electrodes are spaced apart across an extended confinement region of the confinement volume adjacent to the center confinement volume portion;

a first electrode arrangement of the first pair of opposing electrode arrangements and a first electrode arrangement of the second pair of opposing electrode arrangements are associated with a first common surface; and

a second electrode arrangement of the first pair of opposing electrode arrangements and a second electrode arrangement of the second pair of opposing electrode arrangements are associated with a second common surface.

21. A method according to Claim 20, in which the second pair of opposing arrangements of electrodes includes a second arrangement of traveling wave electrodes that are alternately arranged between RF electrodes of the second arrangement of RF electrodes, and in which the confining of the received ions in the second lateral inward direction includes confining the received ions in the extended confinement region in the second lateral inward direction in response to receipt of a variable DC voltage to the traveling wave electrodes of the second arrangement of traveling wave electrodes.
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22. A method according to Claim 18, in which the received and confined ions have opposite polarities.