

ION FOCUSING DEVICE

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Patent Application No. 15/849,417, filed December
5 20, 2017, which is incorporated herein by reference in its entirety.

FIELD

The field is ion focusing devices.

10 ACKNOWLEDGMENT OF GOVERNMENT SUPPORT

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

BACKGROUND

15 Ion manipulation has allowed the discovery of new applications related to material synthesis and analysis, and has fostered the creation of increasingly useful tools and instruments related to, for example, mass spectrometry. However, problems associated with directing and transferring ions have remained.

20 SUMMARY

Methods and apparatus for directing and transferring ions are disclosed. According to an aspect of the disclosed technology, apparatus include a plurality of electrode arrangements spaced apart from each other opposite an ion propagation axis and defining an ion transfer channel that extends along the ion propagation axis that tapers between an input end that is situated to receive ions
25 and an output end that is situated to couple the received ions to an input end of an ion guide. In some examples, the received ions are coupled at the output end to the input end of the ion guide with an electric field that is matched to the input end of the ion guide. In representative examples, the electrode arrangements are arranged in respective electrode arrangement planes, each extending at a respective oblique angle with respect to the ion propagation axis. In some examples, each of the
30 respective oblique angles is less than or equal 60 degrees and greater than or equal 5 degrees. In

further examples, at least one of the electrode arrangements includes a plurality of RF electrodes extending in the direction of the ion propagation axis in the plane of the at least one electrode arrangement so that RF electrodes are situated to direct the ions away from the at least one electrode arrangement, wherein the at least one electrode arrangement includes a plurality of traveling wave electrode sets interspersed between the RF electrodes and extending in the direction of the ion propagation axis in the plane of the at least one electrode arrangement so that the traveling wave electrode sets are situated to direct the ions towards the output end of the ion transfer channel. In some examples, the at least one electrode arrangement is tapered such that there are fewer RF electrodes and traveling wave electrode sets at the output end of the ion transfer channel than at the input end of the ion transfer channel. In further examples, at least one of the electrodes at the input end that is not at the output end is non-rectangular based on an angle defined by the tapering of the at least one electrode arrangement. According to some embodiments, guard electrodes are situated opposite the plurality of RF electrodes and plurality of traveling wave electrode sets of the at least one electrode arrangement so as to direct the ions away from the pair of guard electrodes and into the ion transfer channel between the guard electrodes. In some examples, the guard electrodes comprise an opposing pair of DC electrodes, an opposing pair of RF electrode stacks, or an opposing pair of traveling wave electrode sets. In further examples, each of the traveling wave electrode sets includes a plurality of traveling wave electrodes situated to receive a traveling wave voltage that varies over time so as to direct the ions along toward the output end of the ion transfer channel. In additional examples, the RF electrodes and traveling wave electrodes at the output end of the ion transfer channel are matched in size, shape, RF voltage signal, or traveling wave voltage signal of respective electrodes at the input end of the ion guide. According to some embodiments, the ions directed by the apparatus have the same or different polarities.

According to another aspect of the disclosed technology, methods include positioning a plurality of electrode arrangements at oblique angles opposite an ion propagation axis so as to form a ion transfer channel that tapers between an input end and an output end, and coupling the output end of the ion transfer channel to an input end of an ion optical element so as to direct ions in the ion transfer channel into the ion optical element. In some embodiments, the coupling includes matching an electric field provided by the ion transfer channel at the output end with an electric field provided by the ion optical element. In further embodiments, ions are generated with an ion source and the ions are

collected in the ion transfer channel. In additional examples, methods include directing the ions in the ion transfer channel to the output end with an electric field provided by the plurality of electrode arrangements. In further examples, methods include directing the ions at the output end into the input end of the ion optical element with the matching electric field. In some examples, at least one of the electrode arrangements includes a plurality of RF electrodes and traveling wave electrode sets arranged in a plane and the arrangement is tapered in the plane such that there are fewer RF electrodes and traveling wave electrode sets at the output end of the ion transfer channel than at the input end of the ion transfer channel. In further examples, the electrode arrangements include guard electrodes situated opposite a plurality of RF electrodes and traveling wave electrode sets so as to direct the ions away from the pair of guard electrodes and into the ion transfer channel between the guard electrodes, and wherein the guard electrodes include an opposing pair of DC electrodes, an opposing pair of RF electrode stacks, or an opposing pair of traveling wave electrode sets.

According to a further aspect of the disclosed technology, systems include at least one processor, and one or more computer-readable storage media including stored instructions that, responsive to execution by the at least one processor, cause the system to control electric potentials of RF electrodes and traveling wave electrodes in a plurality of electrode arrangements spaced apart from each other opposite an ion propagation axis and defining an ion transfer channel that extends along the ion propagation axis that tapers between an input end that is situated to receive ions and an output end that is situated to couple the received ions to an input end of an ion guide so that the ions are directed into the ion guide.

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 a top view of an example ion focusing device.

FIG. 1B is a side view of the example ion focusing device shown in FIG. 1A.

FIG. 1C is a perspective view of the example ion focusing device shown in FIGS. 1A-1B.

FIG. 2 is a top view of an example ion focusing device.

FIG. 3 is a top view of another example ion focusing device.

FIGS. 4A-4F are top view schematics of different examples of electrode arrangements.

FIGS. 5A-5B are respective top and side views of another example of an ion focusing device.

FIG. 6 is a top view of another example ion focusing device.

FIG. 7 is a schematic of an ion manipulation system.

5 FIG. 8 is a flowchart of an example method of directing ions.

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
10 “comprises.” Further, the term “coupled” does not exclude the presence of intermediate elements between the coupled items.

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-
15 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 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.

20 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 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
25 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
30 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.

5 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 or channels of various shapes, sizes, and configurations. A direction can correspond to a single path, multiple paths, bi-directional movement,
10 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
15 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 channels to direct ions with minimal or no losses. 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
20 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
25 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
30 confinement volumes includes gases or reactants. Arrangements of RF electrodes and traveling wave

electrodes receive corresponding potentials that allow creation of ion channels in the volume or gap between the electrode arrangements with a broad acceptance aperture so that lossless or substantially lossless coupling of ions to a narrower aperture can be achieved. Collection and coupling can include losses of less than 0.1%, 1%, or 5% of ions injected into a downstream ion optical component (such as an ion guide).

Traveling waves are typically created by dynamically applying DC potentials to a plurality 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 mobilities, including producing ion confinement, lossless transport, and ion separation. In representative examples, traveling waves are used to losslessly direct ions along an ion channel, from a larger aperture to a narrower aperture. One traveling wave 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 ion separation. Traveling wave speed can be varied so as to produce movement and separation, and to gate groups of ions that are directed into subsequent ion manipulation components. Another traveling wave 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 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-1C show an example ion focusing device 100 situated to receive ions 102 having various characteristics (mass, polarity, velocity, etc.) and to direct the ions into an ion optical element, such as an ion guide 104. In representative examples, the ions 102 are collected from an ion source 106 and ion losses are reduced so as to provide efficient ion transfer to the ion guide 104. The ion focusing device 100 collects and transfers the ions 102 to the ion guide 104 with a tapered ion transfer

channel 108 that is defined by a pair of electrode arrangements 110, 112 spaced apart from each other opposite an ion propagation axis 114. The tapering of the ion transfer channel 108 provides a large aperture at an input end 116 to efficiently collect the ions 102 having various trajectories, and a smaller aperture at an output end 118 to couple the ions 102 into an input aperture 120 of the ion guide 104.

5 The tapering can define respective oblique angles θ_1 , θ_2 (or effective angles if the electrode arrangements are not planar) between the respective electrode arrangements 110, 112 and the ion propagation axis 114. In typical examples, θ_1 is equal to θ_2 though non-equal angles are possible. As shown, angles θ_1 , θ_2 are at 30 degrees with respect to the ion propagation axis 114. In further examples, θ_1 , θ_2 are at 5 degrees, 15 degrees, 45 degrees, 60 degrees, or other angles. In representative
10 embodiments, an electric field produced by the electrode arrangements 110, 112 at the output end 118 is synchronized or smoothly matched to an electric field produced by the ion guide 104 at the ion guide input aperture 120. In some examples, the ions 102 can have the same polarities or different polarities. Representative examples of the ion focusing device 100 can substantially relieve engineering constraints associated with precise alignment of ion optics, such as between planar ion guides and ion
15 sources, and therefore can substantially reduce the cost of building ion manipulation platforms.

In some examples, the opposing electrode arrangements 110, 112 are planar and include respective pluralities of radio frequency (RF) electrodes 122a-122h, 124a-124h that extend in the direction of the ion propagation axis 114, e.g., along the planes of the respective electrode arrangements 110, 112 from the input end 116 towards the output end 118. Adjacent electrodes of the
20 RF electrodes 122a-122h, 124a-124h are typically driven out of phase with respect to each other (e.g., 122a, 122c driven in-phase and 122b driven out of phase) so that the ions 102 propagating in the ion transfer channel 108 are directed away from the respective electrode arrangement 110, 112, e.g., as shown with arrows 126, 128. The opposing electrode arrangements 110, 112 can also include respective pluralities of sets of traveling wave electrodes 130a-130g, 132a-132g that also extend in the
25 direction of the ion propagation axis 114. Each of the sets of traveling electrodes 130a-130g, 132a-132g includes respective pluralities of traveling wave electrodes 134 that can be driven at time varying DC voltages and synchronized in the respective plurality so that a traveling wave is formed in the direction of the ion propagation axis 114. The traveling wave electric fields can direct the ions 102 along the ion transfer channel 108 from the input end 116 to the output end 118, e.g., as shown with

arrows 136, 138. The sets of traveling wave electrodes 130a-130g, 132a-132g are typically alternately interspersed between the RF electrodes 122a-122h, 124a-124h.

In representative embodiments, the opposing electrode arrangements 110, 112 include an electrode tapering in the respective electrode planes. The electrode tapering can reduce the number of electrodes at the output end 118 that are presented to the input aperture 120 of the ion guide 104 as compared to the number of electrodes at the input end 106. For example, the outer RF electrodes 122a, 122h can extend shorter lengths than the inner RF electrodes 122b-122g, or can terminate before the output end 118. Similarly, the outer RF electrodes 124a, 124h can extend reduced lengths or terminate before the output end 118. Interspersed sets of traveling wave electrodes 130a, 130g, 132a, 132g can also extend less than the entire length from the input end 106 to the output end 118. In some examples, the number of traveling wave electrodes 134 in the sets of traveling wave electrodes 130a, 130g, 132a, 132g can be the same as or smaller than the number of traveling wave electrodes 134 in the inner sets of traveling wave electrodes 130b-130f, 132b-132f. Various taper shapes or combinations of shapes can be formed and associated with reduced electrode or electrode set lengths, including one or more of trapezoidal, triangular, inward curving, outward curving, asymmetrical, rectangular, etc.

Opposing guard electrodes 140a, 140b are situated adjacent to, and in the plane of, the electrode arrangement 110, and opposing guard electrodes 142a, 142b are situated adjacent to, and in the plane of, the electrode arrangement 112. The guard electrodes 140a, 140b, 142a, 142b are typically biased with a DC voltage so as to direct the ions 102 away from the guard electrodes 140a, 140b, 142a, 142b so as to be situated between the opposing electrode arrangements 110, 112 in the ion transfer channel 108, e.g., in the directions indicated by arrows 144, 146. The guard electrodes 140a-140b, 142a-142b can be shaped to complement a tapered shape of the respective electrode arrangements 110, 112. In typical examples, the electrode arrangements 110, 112 and the guard electrodes 140a, 140b can be formed on printed circuit board, using 3D printing, or other substrates suitable for ion manipulation. Electrode size and spacing can be varied based on electric field requirements for different ions, coupling efficiencies, and input parameters for ion optical elements (e.g., particle energy, density, timing, etc.). Electrode spacing typically provides a minimum non-conductive area between electrodes to reduce the probability of electrical shorts or interference. In typical examples, minimum spacing and electrode size is on the order of millimeters, including as low as about 0.5 mm, though other dimensions are possible. Square and rectangular shapes can simplify construction and

can define device features or boundaries (e.g., sides, apertures, etc.), some of which can be used to register against other ion guides or devices.

The input aperture 120 of the ion guide 104 or ion optical element is coupled or can be coupled to the output end 118 of the ion focusing device 100. In some embodiments, the ion focusing device 100 can be formed as an integral part of the ion guide 104, and in further embodiments, the ion focusing device 100 can be a separate device that can be coupled to various ion optical elements. In particular embodiments, the oblique angles θ_1 , θ_2 between the ion propagation axis 114 and the electrode arrangements 110, 112 can be varied with one or more hinges, translation stages, or other angle varying devices, including with the ion focusing device 100 situated separately or as attached or a part of the ion guide 104. In some examples, the ion guide 104 can include one or more electrode arrangements, such as opposing electrodes arrangements 148, 150, that match one or more characteristics of the respective electrode arrangements 110, 112 so as to smoothly couple the ions 102 from the ion transfer channel 108 to the ion guide 104. In one embodiment, the electrode arrangements 148, 150 include a plurality of RF electrodes 152a-152f, 154a-154f and traveling wave electrode sets 156a-156e, 158a-158e that are shaped and spaced at the input aperture 120 similarly to the RF electrodes 122b-122g, 124b-124g and the traveling wave electrode sets 130b-130f, 132b-132f at the output end 118. The electrodes 154a-154f, 158a-158e are shown parenthetically in FIG. 1B as hidden in the view below the electrodes 152a-152f, 156a-156e. In some examples, the electrode arrangements 148, 150 can respectively contact the electrode arrangements 110, 112 or can respectively continuously extend from the electrode arrangements 110, 112. In representative examples, the electrode arrangements 110, 112 are respectively spaced apart from the electrode arrangements 148, 150.

In some embodiments, an RF voltage signal applied to RF electrodes 122b-122g, 124b-124g of the electrode arrangements 110, 112 can be synchronized or applied similarly to RF electrodes 152a-152f, 154a-154f of the electrode arrangements 148, 150. In further embodiments, a traveling wave voltage signal applied to traveling wave electrode sets 132b-132f, 134b-134f can be synchronized or applied similarly to traveling wave electrode sets 156a-156e, 158a-158e. Representative examples of the ion guide 104 also include DC guard electrodes 160a, 160b, 162a, 162b that are situated to direct the ions 102 received in the ion guide 104 away from lateral sides of the ion guide 104 and between the electrode arrangements 148, 150. In various examples, voltage signals applied to the electrode

arrangements 148, 150 or to other electrodes (not shown) of the ion guide 104 adjacent to the electrode arrangements 148, 150 can be the same or different from the voltage signals applied to the electrode arrangements 110, 112 based on selected ion activity or application in the ion guide 104, such as ion filtering, ion separation, ion gating, mass spectrometry, time-of-flight control, ion beam cross-section variation (e.g., circular, non-circular, elliptical, symmetric, asymmetric, etc.) etc.

In FIG. 2, an ion focusing device 200 includes RF electrodes 202a-202h and traveling wave electrode sets 204a-204g that are situated parallel to each other and at an oblique angle (into the plane of FIG. 2) to an ion propagation axis 206. A set of similar electrodes oppositely situated about the ion propagation axis 206 at a similar oblique angle and that assists with directing collected ions to an ion optical element 208 is omitted for clarity. Outer RF electrodes 202a-202b, 202g-202h and traveling wave electrode sets 204a, 204g extend lengths shorter than inner RF electrodes 202c-202f and traveling wave electrode sets 204b-204f so as to define an electrode tapering between an input end 210 and an output end 212 of the ion focusing device 200. Opposing guard electrodes 214, 216 are also situated to direct ions away from the respective guard electrodes 214, 216 so that the ions are kept within the ion focusing device 200.

FIG. 3 is another example of an ion focusing device 300 having an ion propagation axis 301 and that includes an electrode arrangement 302 having a set 304 of inner RF electrodes and traveling wave electrode sets. The electrode arrangement 302 further includes opposite, tapered outer electrode sets 306a, 306b including respective non-rectangular RF electrodes 308, 310 and non-rectangular traveling wave electrodes 312a-312c, 314a-314c. The ion focusing device 300 can be situated to collect ions from an ion source and to direct the collected ions to an ion guide 316 situated downstream along the ion propagation axis 301.

FIGS. 4A-4F are different examples of tapered planar electrode arrangements 400a-400f that can be used with one or more other planar electrode arrangements situated at angles in relation to respective ion propagation axes 402a-402f to form respective tapered ion focusing channels. Each of the electrode arrangements 400a-400f can include a plurality of longitudinally extending RF electrodes 404a-404f and traveling wave electrode sets 406a-406f that extend various lengths. The RF electrodes 404a-404f generally maintain ions between the respective electrode arrangements 400a-400f and other electrode arrangements of the tapered ion focusing channels. The traveling wave sets 406a-406f are generally situated to move the ions in the ion focusing channels in the direction of the ion propagation

axes 402a-402f. The electrode arrangement 400a is arranged in a trapezoidal configuration extending from a channel input 408a to a channel output 410a that can be coupled with subsequent ion manipulation elements. Sides of the electrode arrangement 400b curve inwardly between a channel input 408b and a channel output 410b. In the electrode arrangement 400c, one side of the electrode arrangement 400c is tapered between a channel input 408c and a channel output 410c, and an opposite side extends parallel to the RF electrodes 404c, the traveling wave electrode sets 406c. The electrode arrangement 400d is similar to the electrode arrangement 400b except that opposite tapered sides curve outward between a channel input 408d and a channel output 410d. The electrode arrangement 400e shows an asymmetric configuration that includes opposite tapered inward-curving and outward-curving sides extending between a channel input 408e and a channel output 410e. Various combinations of electrode arrangement geometries can be formed as well, and electrode arrangement 400f shows one such example with a rectangular electrode arrangement portion 412f extending from a channel input 408f a predetermined length and a trapezoidal electrode arrangement portion 414f extending from an end of the rectangular electrode arrangement portion 412f to a channel output 410f.

FIGS. 5A-5B depict an example of an ion focusing device 500 that includes guard electrode sets 502a, 502b situated at opposite ends of opposing electrode arrangements 504a, 504b so as to define an ion focusing channel 506 between an input aperture 508 and an output aperture 510. The guard electrodes 502a, 502b include respective pluralities of adjacent RF electrodes 512 forming stacked arrangements that are situated to direct ions into the ion focusing channel 506, e.g., in the direction of arrows 514a, 514b. In typical examples, the alternate RF electrodes are biased out of phase so as to provide the directing of the ions into the interior of the ion focusing channel 506. As shown in FIG. 5B, the RF electrodes 512 of the guard electrode set 502a generally extend parallel to an ion propagation axis 516. In typical examples, the RF electrodes of the guard electrode 502b can also extend parallel to the ion propagation axis 516. Also, as shown in FIG. 5B, the RF electrodes 512 can define an electrode tapering towards the output aperture 510. In some examples, all or additional RF electrodes of the guard electrode sets 502a, 502b can extend equal lengths between the input aperture 508 and the output aperture 510. In additional examples, the RF electrodes 512 of one or both of the guard electrode sets 502a, 502b are not parallel to each other. For example, one or more of the RF electrodes 512 can be parallel to planes defined by one of the opposing electrode arrangements 504a, 504b or at other angles.

In FIG. 6, an ion focusing device 600 is shown that includes a planar electrode arrangement 602 that includes RF electrodes 604a-604h and longitudinal traveling wave sets 606a-606g arranged similar to the arrangement RF electrodes 202a-202h and traveling wave electrode sets 204a-204g shown in FIG. 2. The ion focusing device 600 is generally situated to direct ions along an ion propagation axis 608 between an input aperture 610 and an output aperture 612. The ion propagation axis 608 is generally arranged at an oblique angle (into the plane of FIG. 6) to the planar electrode arrangement 602, and a similar opposing electrode arrangement (below the electrode arrangement 602 and not shown) can also be arranged at an angle with respect to the ion propagation axis so as to define a tapering of an ion propagation channel 613 defined between the electrode arrangement 602 and the opposing electrode arrangement between the input aperture 610 and output aperture 612. Opposing guard electrodes 614a, 614b are also situated opposite the electrode arrangement 602 and include alternating RF electrodes 616a-616d, 618a-618d and interspersed traveling wave electrodes 620a-620d, 622a-622d. The RF electrodes 616a-616d, 618a-618d direct ions between the planar electrode arrangement 602 and the opposing electrode arrangement (e.g., into the plane of FIG. 6) so that the ions are kept in the ion propagation channel 613. The traveling wave electrodes 620a-620d, 622a-622d are situated to direct the ions towards the ion propagation axis 608, e.g., in the direction of arrows 624a, 624b, so that ions can also be directed according to a tapering of the electrodes in the plane of the planar electrode arrangement 602 towards the output aperture 612.

FIG. 7 is a schematic of an ion collection system 700 that includes an ion focusing device 702 that is situated to collect ions 704 from an ion source 706 and to direct the ions 704 into an ion optical element 708. The ion focusing device 702 includes opposing electrode arrangements 710, 712 situated at an angle with respect to an ion optical axis 714 and each situated with a plurality of RF electrodes and traveling wave electrode sets to guide the ions 704 in an ion focus channel 716 from an input end 718 to an output end 720 to an input end 722 of the ion optical element 708. The ion optical element 708 can include opposing electrode arrangements 711, 713 that can be similar to or different from the opposing electrode arrangements 710, 712. A pair of guard electrodes (not shown) can also be situated to direct the ions 704 into the ion focus channel 716 or to prevent the ions 704 from leaving the ion focus channel 716 into or out of the plane of FIG. 7.

The ion collection system 700 also includes an ion control system environment 724 coupled to the ion focusing device 702, ion source 706, and ion optical element 708 that is operable to control ion

collection and ion manipulation. The ion control system environment 724 include one or more computing devices that include at least a processor 726 and a memory 728. Computing devices can include desktop or laptop computers, mobile devices, tablets, logic controllers, etc. The processor 726 can include one or more CPUs, GPUs, ASICs, PLCs, FPGAs, PLDs, CPLDs, etc., that can perform
5 various data processing or I/O functions associated with the ion control system environment 724. The memory 728 can be volatile or non-volatile (e.g., RAM, ROM, flash, hard drive, optical disk, etc.) and fixed or removable and is coupled to the processor 726. The memory 728 can provide storage capacity for one or more computer-readable media. One or more system buses 730 can provide a communication path between various environment components. The ion control system environment
10 724 can also be situated in a distributed form so that applications and tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules and logic can be located in both local and remote memory storage devices.

The ion control system environment 724 can include RF voltage control logic 732 that controls
15 the electric potential applied to the RF electrodes of the electrode arrangements 710, 712. An RF phase delay 734 can be used for alternate adjacent RF electrodes in the electrode arrangements 710, 712 so that a selected phase delay (e.g., 180 degrees) can be applied between adjacent RF electrodes. In some examples, the RF voltage control logic 732 can also control the electric potential applied to RF electrodes of the opposing RF electrode arrangements 711, 713 and such applied voltage can be
20 synchronized with a zero delay or non-zero delay with selected RF electrodes of the electrode arrangements 710, 712, such as those that are longitudinally matched at the output end 722 of the ion focusing device 702 and the input end of the ion optical element 708. In further examples, the ion control system environment 724 can detect or receive an ion guide voltage 736 from the ion optical element 708 and apply an RF voltage to the RF electrodes of the electrode arrangements 710, 712
25 based on RF voltage characteristics (e.g., phase, frequency, amplitude) of the ion guide voltage 736. In additional examples, a traveling wave voltage control logic 738 can control traveling wave electric potentials that are applied to traveling wave electrodes of the electrode arrangements 710, 712 so as to direct the ions 704 towards the output end 720. In some embodiments, traveling wave electric potentials can also be controlled for traveling wave electrode sets of electrode arrangements 711, 713
30 in the ion optical element 708. In some examples, traveling wave characteristics can be synchronized

between the electrode arrangements 710, 711 and electrode arrangements 712, 713 so as to form a smooth or continuous traveling wave coupling between the ion focusing device 702 and the ion optical element 708. In additional embodiments, the ion control system environment 724 can include an ion guide gate logic 740 that controls generation and/or emission of ions from the ion source 706. The ion guide gate logic 740 can also be synchronized to the traveling wave voltage control logic 738 so as to queue or position the ions 704 in the ion focusing device 702 so that groups of the ions 704 are controllably released or directed into the input end 722 of the ion optical element 708. In some examples, various voltage waveforms, ion characteristics, or other system parameters or performance outputs can be displayed on a display 742.

FIG. 8 shows a method 800 for directing ions. At 802, a plurality of typically planar electrode arrangements are positioned oppositely at oblique angles to an ion propagation axis so as to form a ion transfer channel that tapers between an input end and an output end of the ion transfer channel. The tapered ion transfer channel can be used to collect ions from an ion source and to transmit the ions, including losslessly in some examples, to an ion optical element. At 804, the output end of the ion transfer channel is coupled to an input end of the ion optical element so that ions in the ion transfer channel can be directed through the ion transfer channel and into the ion optical element. In representative embodiments, at 806, an electric field provided in the ion transfer channel by the electrode arrangements at the output end is matched to an electric field provided by the ion optical element at the input of the ion optical element.

Having described and illustrated the principles of the disclosed technology with reference to the illustrated embodiments, it will be recognized that the illustrated embodiments can be modified in arrangement and detail without departing from such principles. For instance, elements of the illustrated embodiments shown in software may be implemented in hardware and vice-versa. Also, the technologies from any example can be combined with the technologies described in any one or more of the other examples. It will be appreciated that procedures and functions such as those described with reference to the illustrated examples can be implemented in a single hardware or software module, or separate modules can be provided. The particular arrangements above are provided for convenient illustration, and other arrangements can be used.

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 of the appended
5 claims.

We claim:

1. An ion focusing device, comprising:

a first surface extending along a first axis and a second surface extending along a second axis, the first and second surfaces extending from an input end to an output end of the ion focusing device and defining a space therebetween dimensioned to receive ions, the first axis arranged at a first angle with respect to an ion propagation axis and the second axis arranged at a second angle with respect to the ion propagation axis, the first surface includes an electrode arrangement comprising:

a first plurality of inner electrodes including:

a first plurality of electrodes extending along the first axis, the first plurality of electrodes comprising a first electrode configured to receive a first radiofrequency (RF) voltage and a second electrode configured to receive a second RF voltage, the second electrode adjacent to the first electrode; and

a second plurality of segmented electrodes arranged along the first axis between or adjacent to the first plurality of electrodes, the second plurality of segmented electrodes configured to receive a first plurality of voltages and generate a first traveling wave configured to travel along the first axis; and

first and second outer electrode sets positioned on opposing lateral sides of the first surface, each outer electrode set including:

at least one RF electrode; and

at least one segmented traveling wave electrode;

wherein the outer electrode sets are arranged and configured to define an input width and an output width for the electrode arrangement, wherein the output width is smaller than the input width; and

wherein the electrode arrangement focuses the received ions along the ion propagation axis as the ions traverse from the input end to the output end of the ion focusing device.

2. The ion focusing device of claim 1, wherein the second surface includes a second plurality of inner electrodes comprising:

a third plurality of electrodes extending along the second axis, the third plurality of electrodes comprising a third electrode configured to receive a third radiofrequency (RF) voltage and a fourth electrode configured to receive a fourth RF voltage, the third electrode adjacent to

the fourth electrode; and

a fourth plurality of segmented electrodes arranged along the first axis between or adjacent to the third plurality of electrodes, the fourth plurality of segmented electrodes configured to receive a second plurality of voltages and generate a second traveling wave
5 configured to travel along the second axis.

3. The ion focusing device of claim 1, wherein the first and second outer electrode sets each include:

at least one non-rectangular RF electrode; and

at least one non-rectangular traveling wave electrode.

10 4. The ion focusing device of claim 1, wherein the first and second axis are arranged at an angle of zero degrees with respect to the ion propagation axis.

5. The ion focusing device of claim 1, wherein the first and the second surfaces are separated by an input distance at the input end and an output distance at the output end.

6. The ion focusing device of claim 5, wherein the input distance is greater than the output
15 distance.

7. The ion focusing device of claim 5, wherein the first electrode extends from the input end to the output end along the first axis, wherein the first electrode has a first width at the input end and a second width at the output end, the first width greater than the second width.

8. The ion focusing device of claim 5, wherein the first surface is operatively coupled to an
20 ion source at the input end and an ion transfer channel at the output end.

9. The ion focusing device of claim 8, wherein the first traveling wave is configured to direct ions from the ion source to the ion transfer channel along the ion propagation axis.

10. The ion focusing device of claim 1, wherein the first surface comprises a first guard electrode located at a first outer end and a second guard electrode located at a second outer end
25 of the first plurality of inner electrodes, wherein the first guard electrode and the second guard electrode are configured to generate a guard electric field that constrains ion motion along a lateral direction transverse to the ion propagation axis.

11. The ion focusing device of claim 10, wherein at least one of the first guard electrode and the second guard electrode is configured to receive a DC voltage.
12. The ion focusing device of claim 1, wherein the first surface comprises a first plurality of guard electrodes located at a first outer end of the first plurality of inner electrodes, wherein the first plurality of guard electrodes is configured to generate a first transverse traveling wave along a lateral direction transverse to the ion propagation axis.
13. The ion focusing device of claim 12, wherein a first set of guard electrodes of the first plurality of guard electrodes is configured to receive a plurality of guard RF voltages and generate a pseudopotential that inhibits ions from approaching the first plurality of guard electrodes.
14. The ion focusing device of claim 12, wherein a second set of guard electrodes of the first plurality of guard electrodes configured to receive a third plurality of voltages and generate the first transverse traveling wave.
15. The ion focusing device of claim 12, wherein the first surface comprises a second plurality of guard electrodes located at a second outer end of the first plurality of inner electrodes, wherein the second plurality of guard electrodes is configured to generate a second transverse traveling wave along the lateral direction transverse to the ion propagation axis.
16. The ion focusing device of claim 1, wherein the first RF voltage and the second RF voltage are phase-shifted with respect to one another.
17. The ion focusing device of claim 1, wherein the output width and configuration of the outer electrode sets is such that the electric field provided by the electrode arrangement matches an electric field for an ion guide positioned adjacent to the output end of the ion focusing device.
18. A method comprising:
injecting ions within a space defined between a first surface extending along a first axis and a second surface extending along a second axis, each surface extending from an input end to an output end, the first axis arranged at a first angle with respect to an ion propagation axis and the second axis arranged at a second angle with respect to the ion propagation axis, the first

surface includes an electrode arrangement comprising:

a first plurality of inner electrodes including:

a first plurality of electrodes extending along the first axis, the first plurality of electrodes comprising a first electrode and a second electrode adjacent to the first electrode; and

5 a second plurality of segmented electrodes arranged along the first axis between or adjacent to the first plurality of electrodes; and

first and second outer electrode sets positioned on opposing lateral sides of the first surface, each outer electrode set including:

at least one RF electrode; and

10 at least one segmented traveling wave electrode;

wherein the outer electrode sets are arranged and configured to define an input width and an output width which is smaller than the input width for an electrode arrangement;

applying a first RF voltage to the first electrode of the first plurality of electrodes, and a second RF voltage to the second electrode of the first plurality of electrodes;

15 applying a first plurality of voltages to the second plurality of segmented electrodes and generating a first traveling wave configured to travel along the first axis;

applying an RF voltage to the at least one RF electrode associated with the first and second outer electrode sets; and

20 applying a second plurality of voltages to the at least one traveling wave electrode associated with the first and second outer electrode sets;

wherein application of the RF and traveling wave voltages to the electrode arrangement focuses the ions along the ion propagation axis when traversing from the input end to the output end.

19. The method of claim 18, wherein the first electrode and the second electrode are
25 configured to generate a pseudopotential that inhibits ions from approaching the first surface.

20. The method of claim 18, wherein the second surface includes a second plurality of inner electrodes comprising:

a third plurality of electrodes extending along the second axis, the third plurality of electrodes comprising a third electrode configured to receive a third radiofrequency (RF) voltage
30 and a fourth electrode configured to receive a fourth RF voltage, the third electrode adjacent to

the fourth electrode; and

a fourth plurality of segmented electrodes arranged along the first axis between or adjacent to the third plurality of electrodes, the fourth plurality of segmented electrodes configured to receive a second plurality of voltages and generate a second traveling wave

5 configured to travel along the second axis.

21. The method of claim 18, wherein each outer electrode set includes:

at least one non-rectangular RF electrode; and

at least one non-rectangular traveling wave electrode.

22. The method of claim 18, wherein the first and second axis are arranged at an angle of
10 zero degrees with respect to the ion propagation axis.

23. The method of claim 18, wherein the first and the second surfaces extend from an input end on the ion propagation axis to an output end on the ion propagation axis, the first and the second surfaces separated by an input distance at the input end and an output distance at the output end.

15 24. The method of claim 23, wherein the first electrode extends from the input end to the output end along the first axis, wherein the first electrode has a first width at the input end and a second width at the output end, the first width greater than the second width.

25. The method of claim 23, further comprising operatively coupling the first surface to an ion source at the input end and an ion transfer channel at the output end.