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Clemmer et al.

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(45) **Date of Patent: *Sep. 29, 2020**

(54) **CLOSED PATH ION MOBILITY SPECTROMETER HAVING A COMMON ION INLET AND OUTLET**

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(73) Assignee: **The Trustees Of Indiana University**, Indianapolis, IN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

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(Continued)

(51) **Int. Cl.**

G01N 27/62 (2006.01)
H01J 49/26 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***G01N 27/622*** (2013.01); ***H01J 49/022*** (2013.01); ***H01J 49/26*** (2013.01); ***H01J 49/443*** (2013.01); ***H01J 49/46*** (2013.01)

(58) **Field of Classification Search**

CPC G01N 27/622; H01J 49/022; H01J 49/26; H01J 49/443; H01J 49/46

(Continued)

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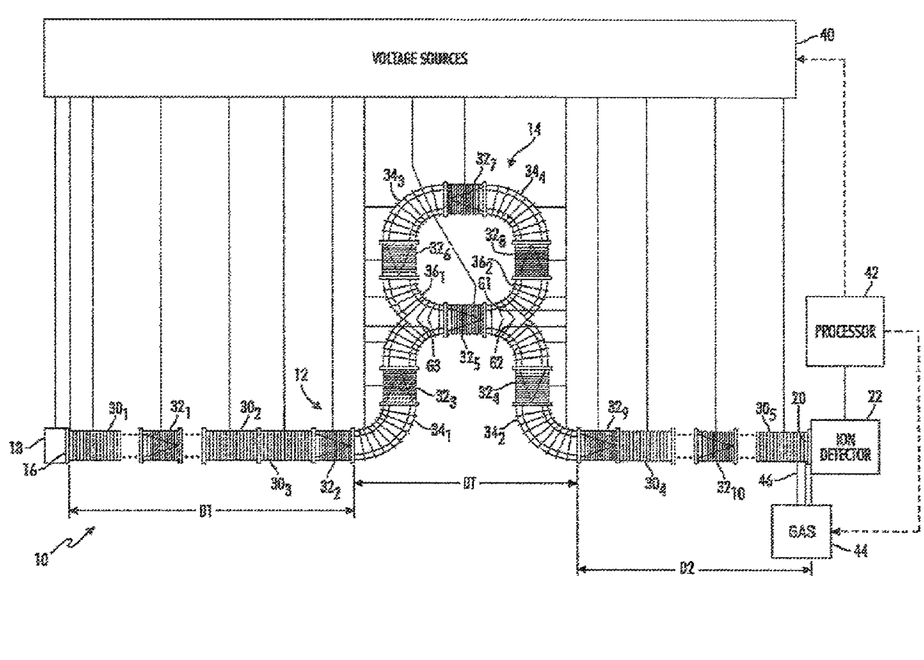
Assistant Examiner — Hanway Chang
(74) *Attorney, Agent, or Firm* — Barnes & Thornburg, LLP

(57) **ABSTRACT**

An ion mobility spectrometer includes a drift tube responsive to application of at least a first voltage to establish a first electric field therein configured to cause ions within the drift tube to move along and about the drift tube while separating from one another as a function of ion mobility, and a transition region coupled to opposed ends of the first drift tube such that the drift tube and the transition region together define a closed path. The transition region is responsive to application of at least a second voltage to cause the ions to move along and about the closed path, to application of at least a third voltage to selectively pass ions into the drift tube and to application of at least a fourth voltage to selectively pass ions out of the drift tube.

20 Claims, 15 Drawing Sheets



Related U.S. Application Data

continuation-in-part of application No. 15/023,575, filed as application No. PCT/US2014/056970 on Sep. 23, 2014, now Pat. No. 9,683,965.

(60) Provisional application No. 61/882,891, filed on Sep. 26, 2013.

(51) **Int. Cl.**

H01J 49/44	(2006.01)
H01J 49/46	(2006.01)
H01J 49/02	(2006.01)

(58) **Field of Classification Search**
USPC 250/281, 282, 286, 287, 288, 290, 291
See application file for complete search history.

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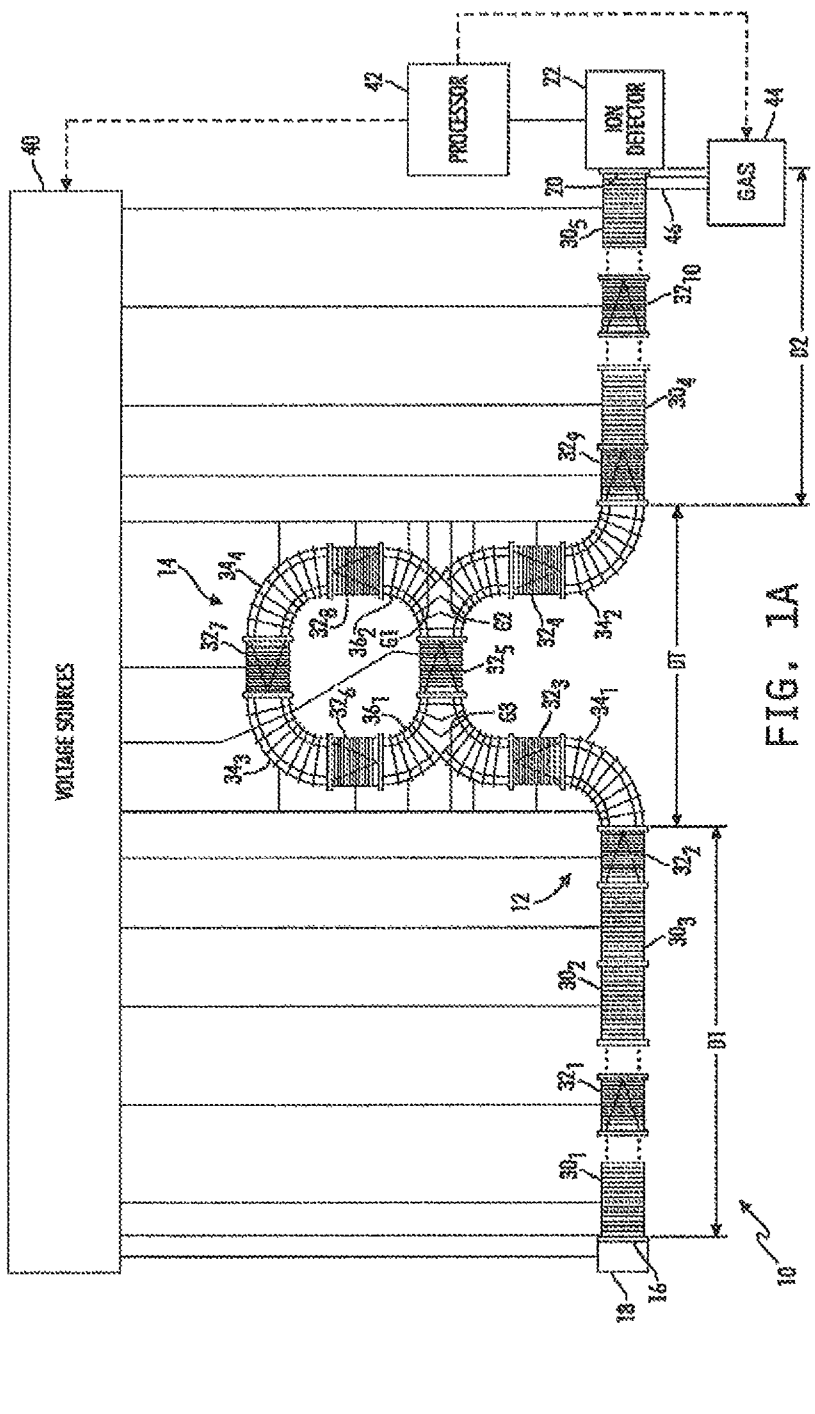


FIG. 1A

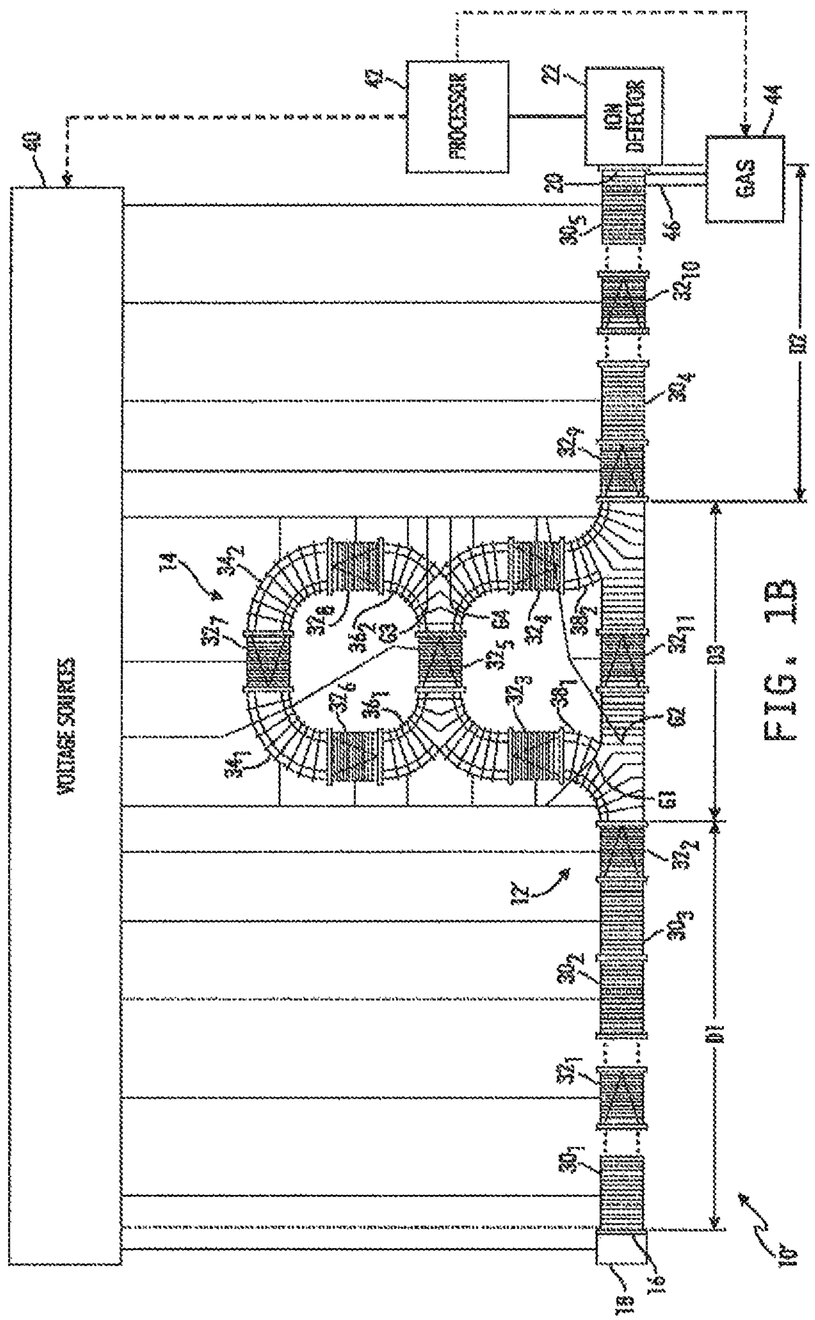


FIG. 1B

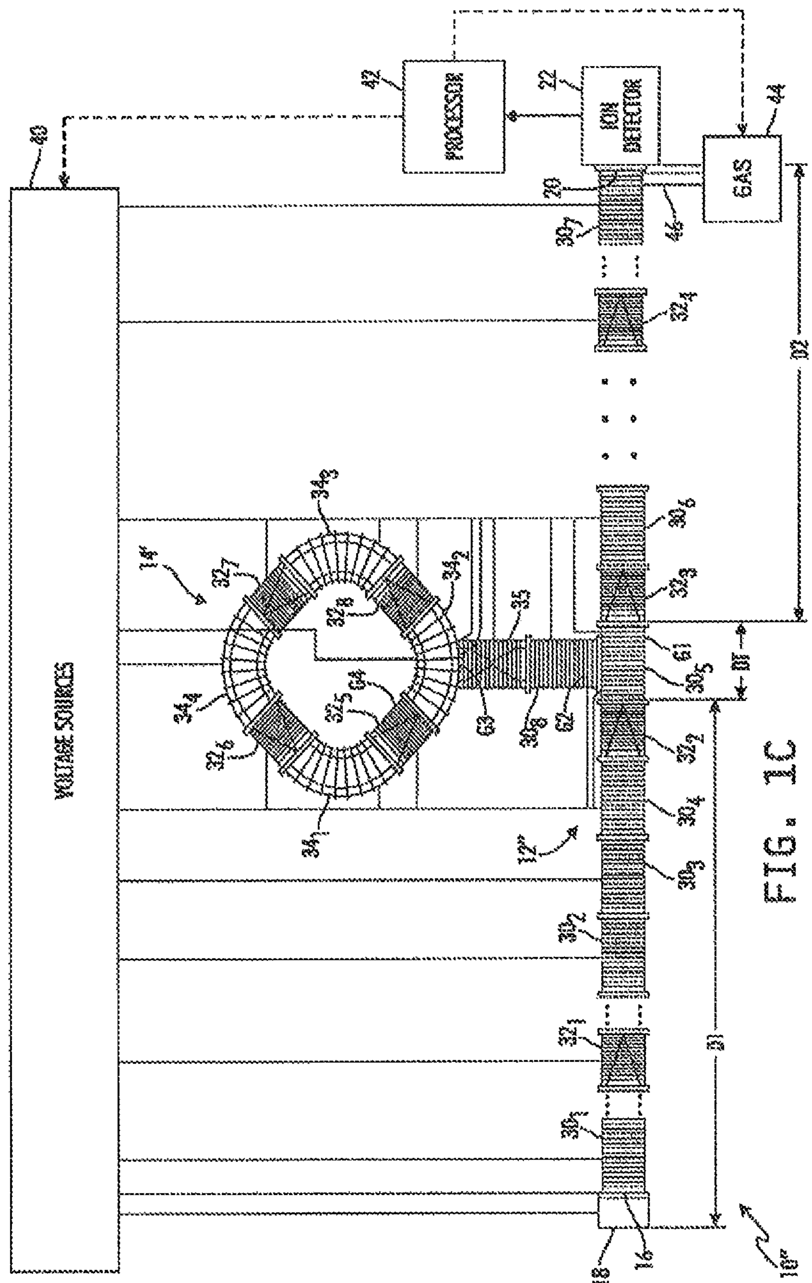


FIG. 1C

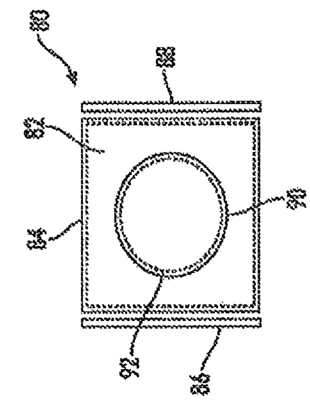


FIG. 1F

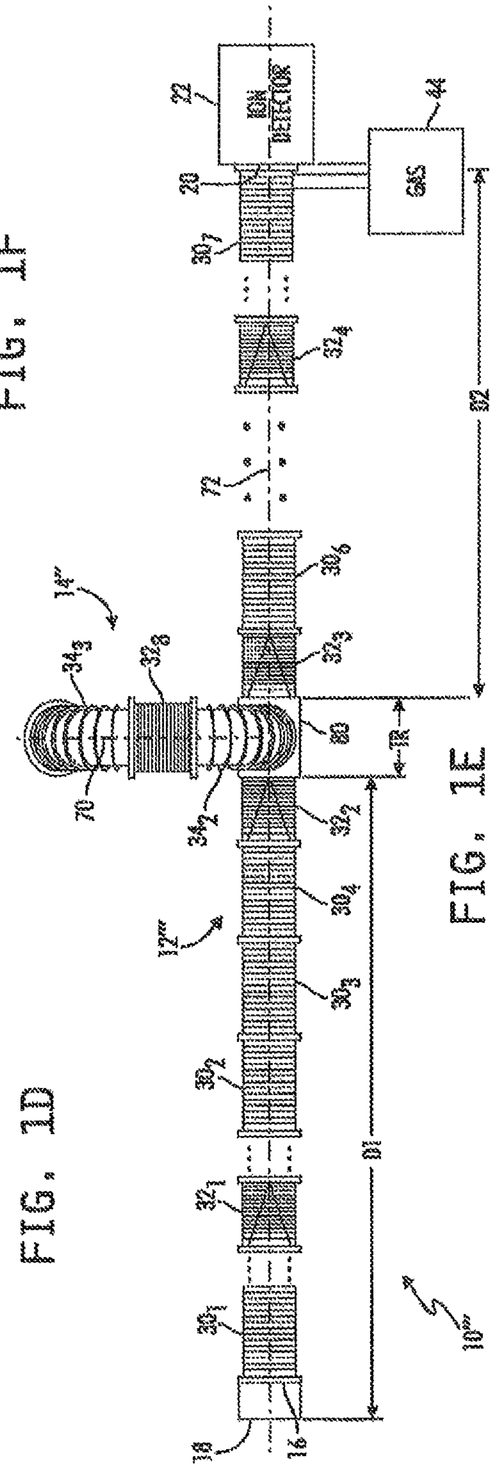


FIG. 1E

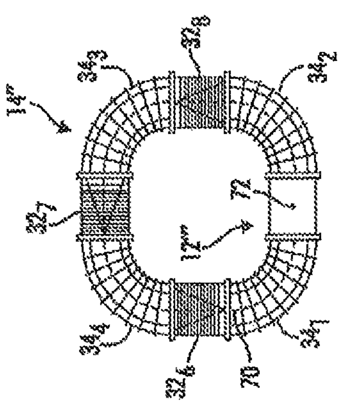


FIG. 1D

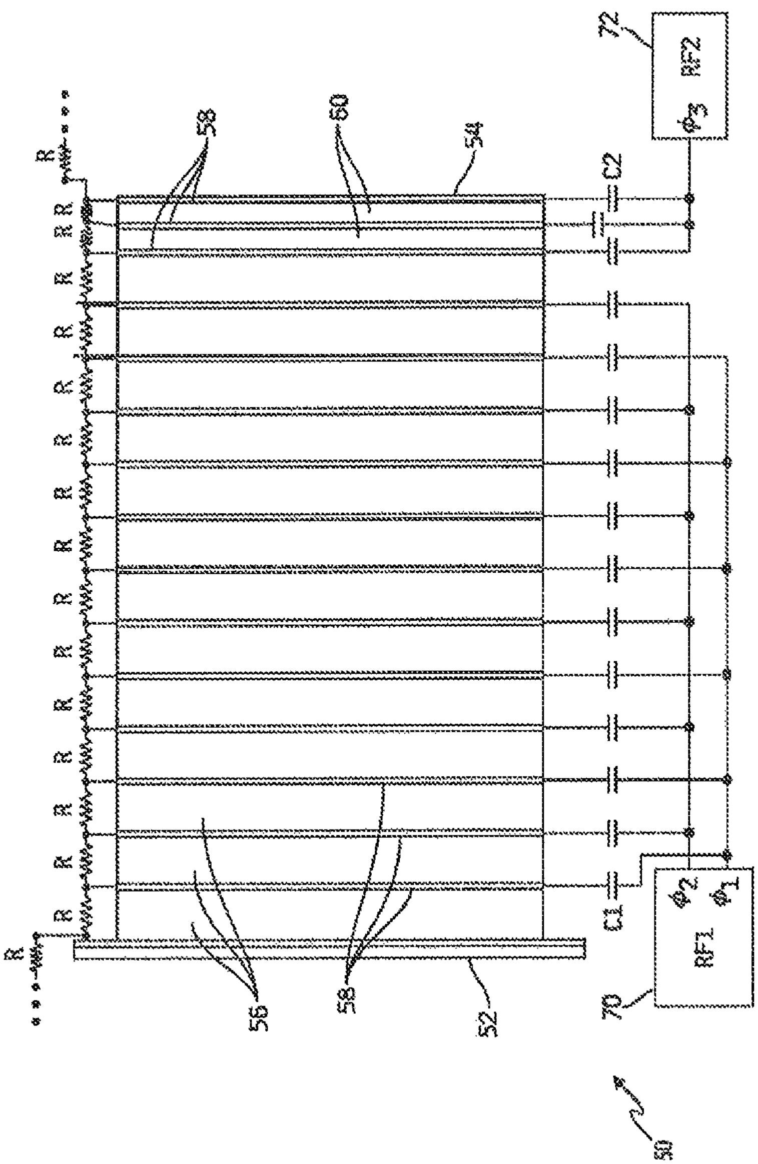


FIG. 2

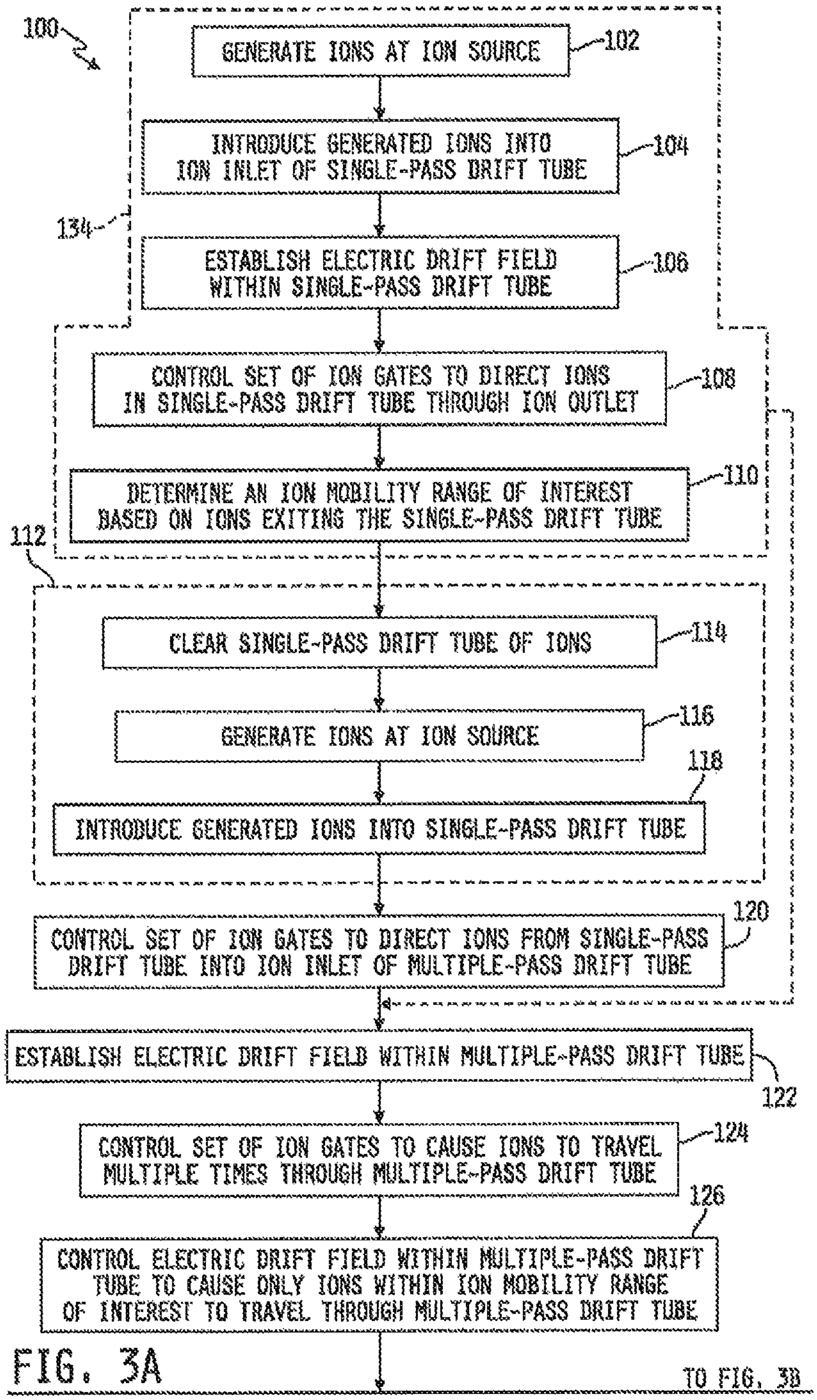

100
GENERATE IONS AT ION SOURCE
102
INTRODUCE GENERATED IONS INTO ION INLET OF SINGLE-PASS DRIFT TUBE
104
134
ESTABLISH ELECTRIC DRIFT FIELD WITHIN SINGLE-PASS DRIFT TUBE
106
CONTROL SET OF ION GATES TO DIRECT IONS IN SINGLE-PASS DRIFT TUBE THROUGH ION OUTLET
108
DETERMINE AN ION MOBILITY RANGE OF INTEREST BASED ON IONS EXITING THE SINGLE-PASS DRIFT TUBE
110
112
CLEAR SINGLE-PASS DRIFT TUBE OF IONS
114
GENERATE IONS AT ION SOURCE
116
118
INTRODUCE GENERATED IONS INTO SINGLE-PASS DRIFT TUBE
120
CONTROL SET OF ION GATES TO DIRECT IONS FROM SINGLE-PASS DRIFT TUBE INTO ION INLET OF MULTIPLE-PASS DRIFT TUBE
ESTABLISH ELECTRIC DRIFT FIELD WITHIN MULTIPLE-PASS DRIFT TUBE
122
CONTROL SET OF ION GATES TO CAUSE IONS TO TRAVEL MULTIPLE TIMES THROUGH MULTIPLE-PASS DRIFT TUBE
124
126
CONTROL ELECTRIC DRIFT FIELD WITHIN MULTIPLE-PASS DRIFT TUBE TO CAUSE ONLY IONS WITHIN ION MOBILITY RANGE OF INTEREST TO TRAVEL THROUGH MULTIPLE-PASS DRIFT TUBE
TO FIG. 3B

FIG. 3A

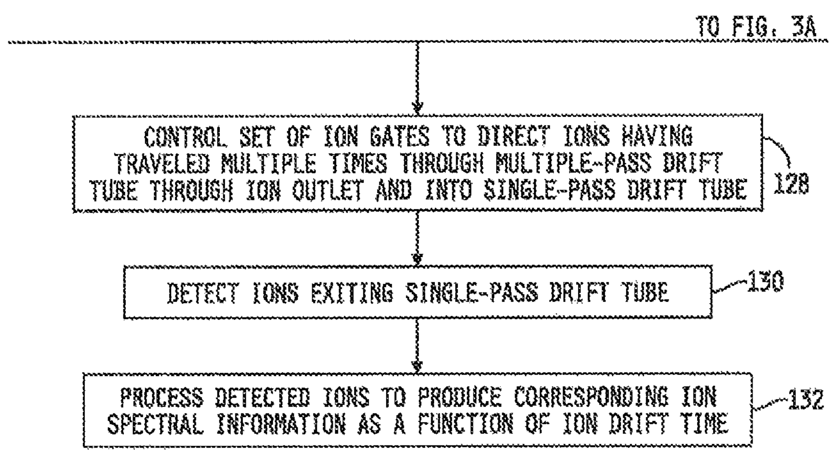

TO FIG. 3A
CONTROL SET OF ION GATES TO DIRECT IONS HAVING TRAVELED MULTIPLE TIMES THROUGH MULTIPLE-PASS DRIFT TUBE THROUGH ION OUTLET AND INTO SINGLE-PASS DRIFT TUBE
128
DETECT IONS EXITING SINGLE-PASS DRIFT TUBE
130
PROCESS DETECTED IONS TO PRODUCE CORRESPONDING ION SPECTRAL INFORMATION AS A FUNCTION OF ION DRIFT TIME
132

FIG. 3B

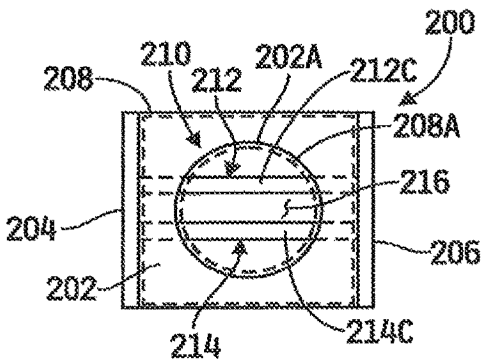


FIG. 4A

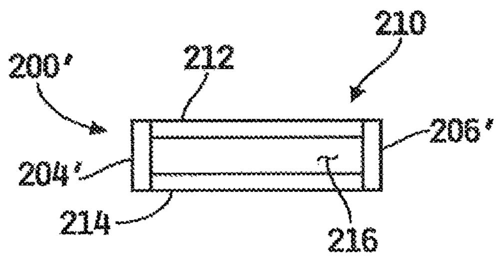


FIG. 4B

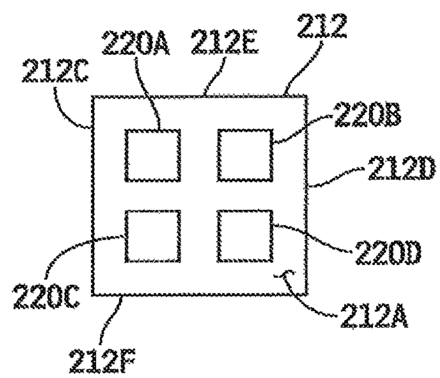


FIG. 5

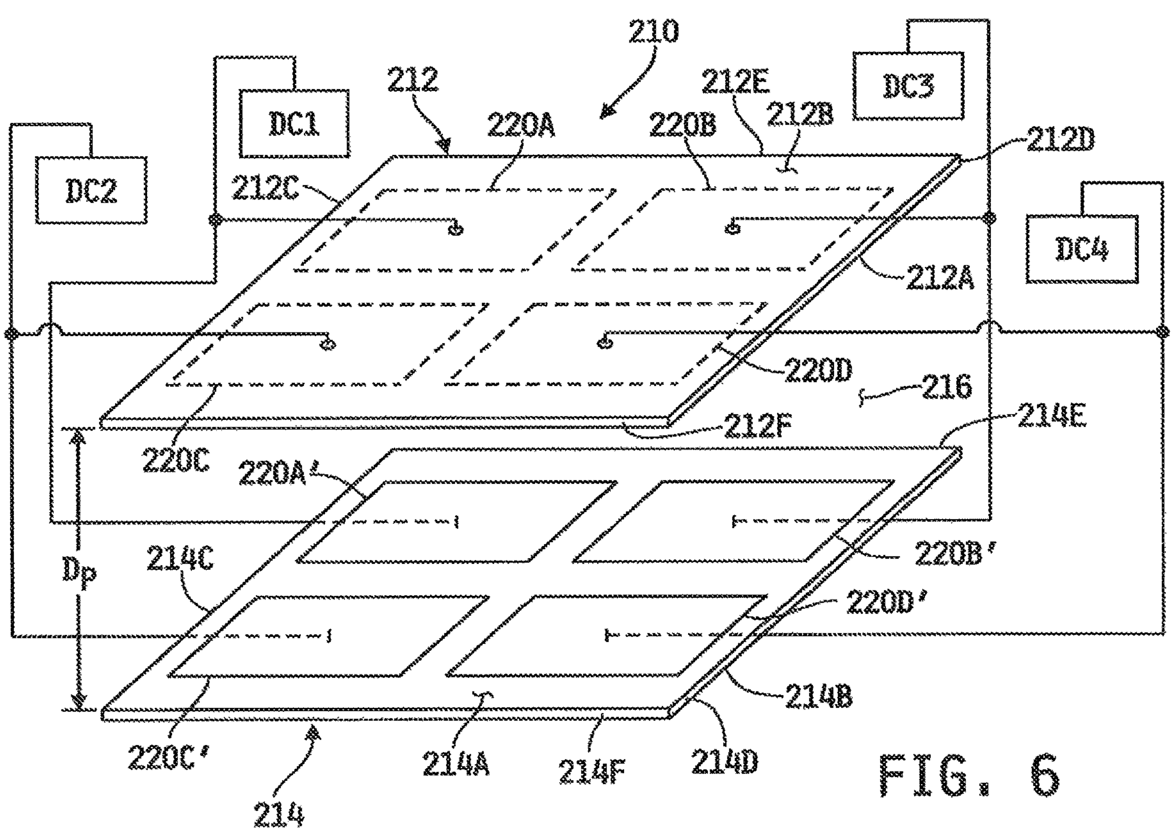


FIG. 6

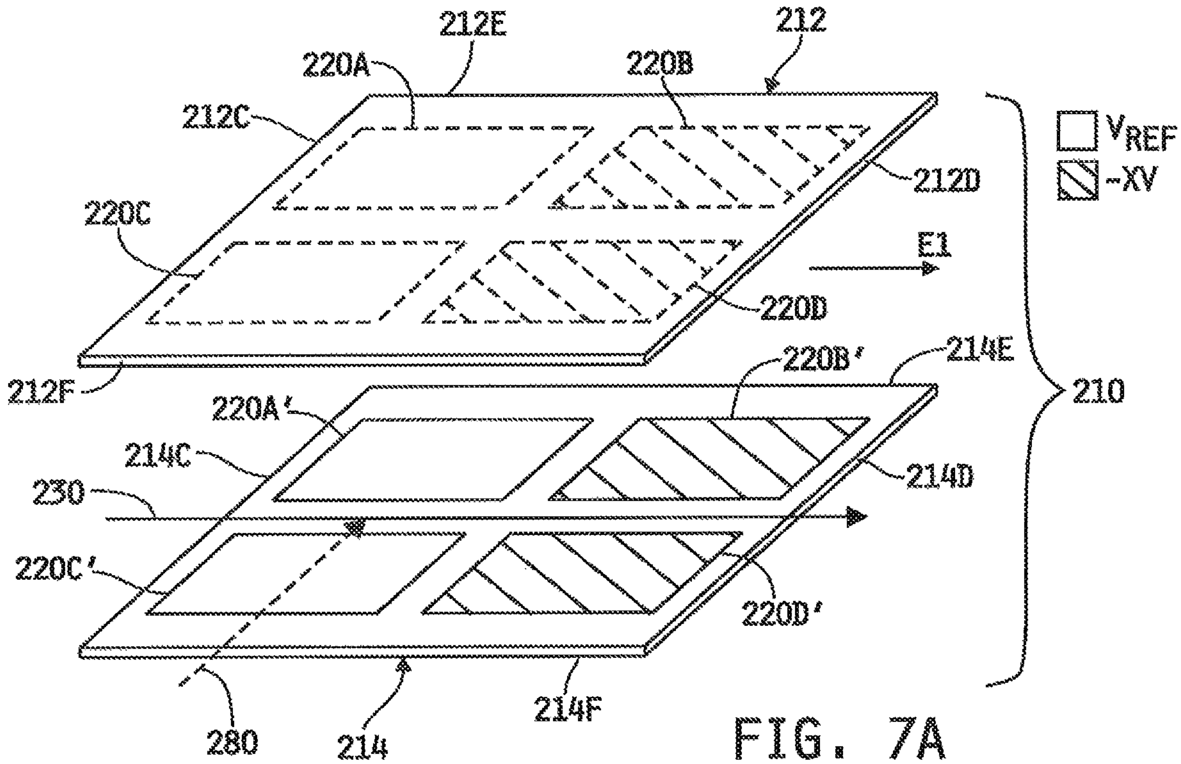

212E
212
220A
220B
212C
V_{REF}
212D
-XV
220C
E1
220D
212F
220B'
214E
220A'
210
214C
214D
230
220C'
220D'
280
214
214F

FIG. 7A

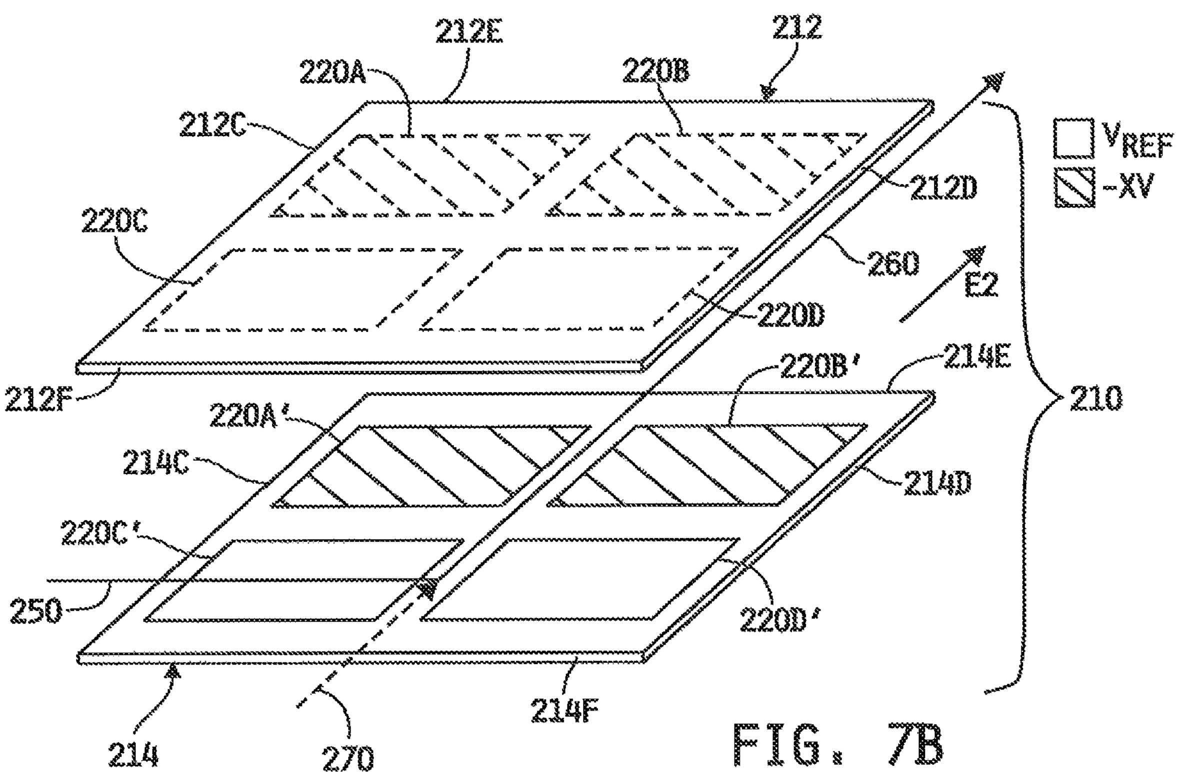

212E
212
220A
220B
212C
V_{REF}
212D
-XV
220C
260
E2
220D
212F
220B'
214E
220A'
210
214C
214D
220C'
250
220D'
214
214F
270

FIG. 7B

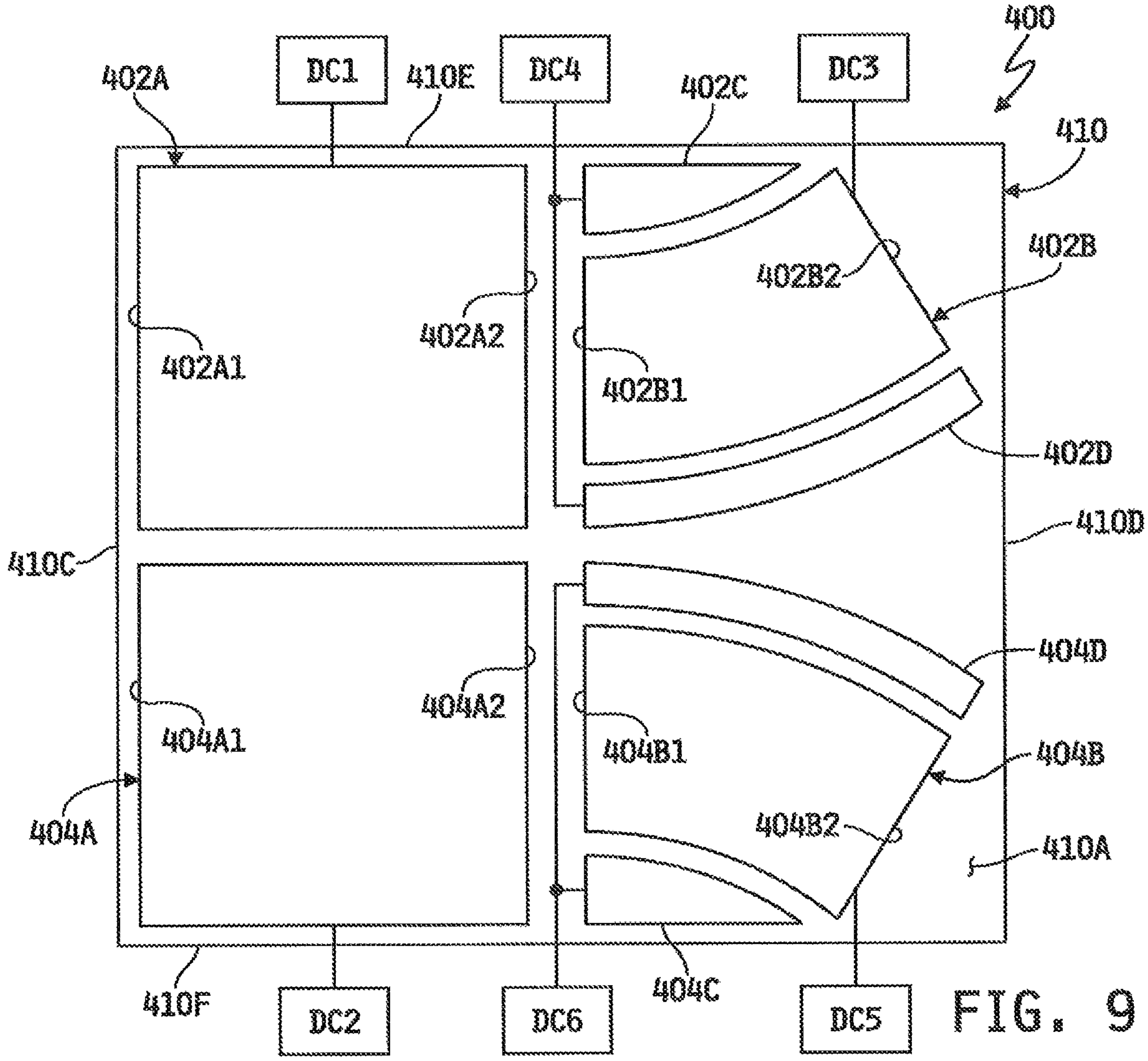

400
410
402A
DC1
410E
DC4
402C
DC3
402B
402B2
402A1
402A2
402B1
402D
410C
410D
404D
404A1
404A2
404B1
404B
404A
404B2
410A
410F
DC2
DC6
404C
DC5

FIG. 9

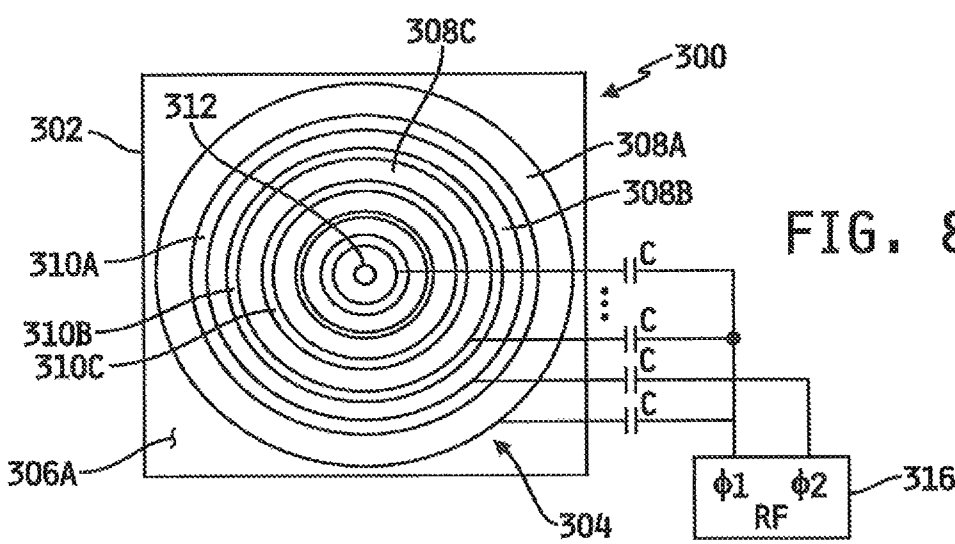
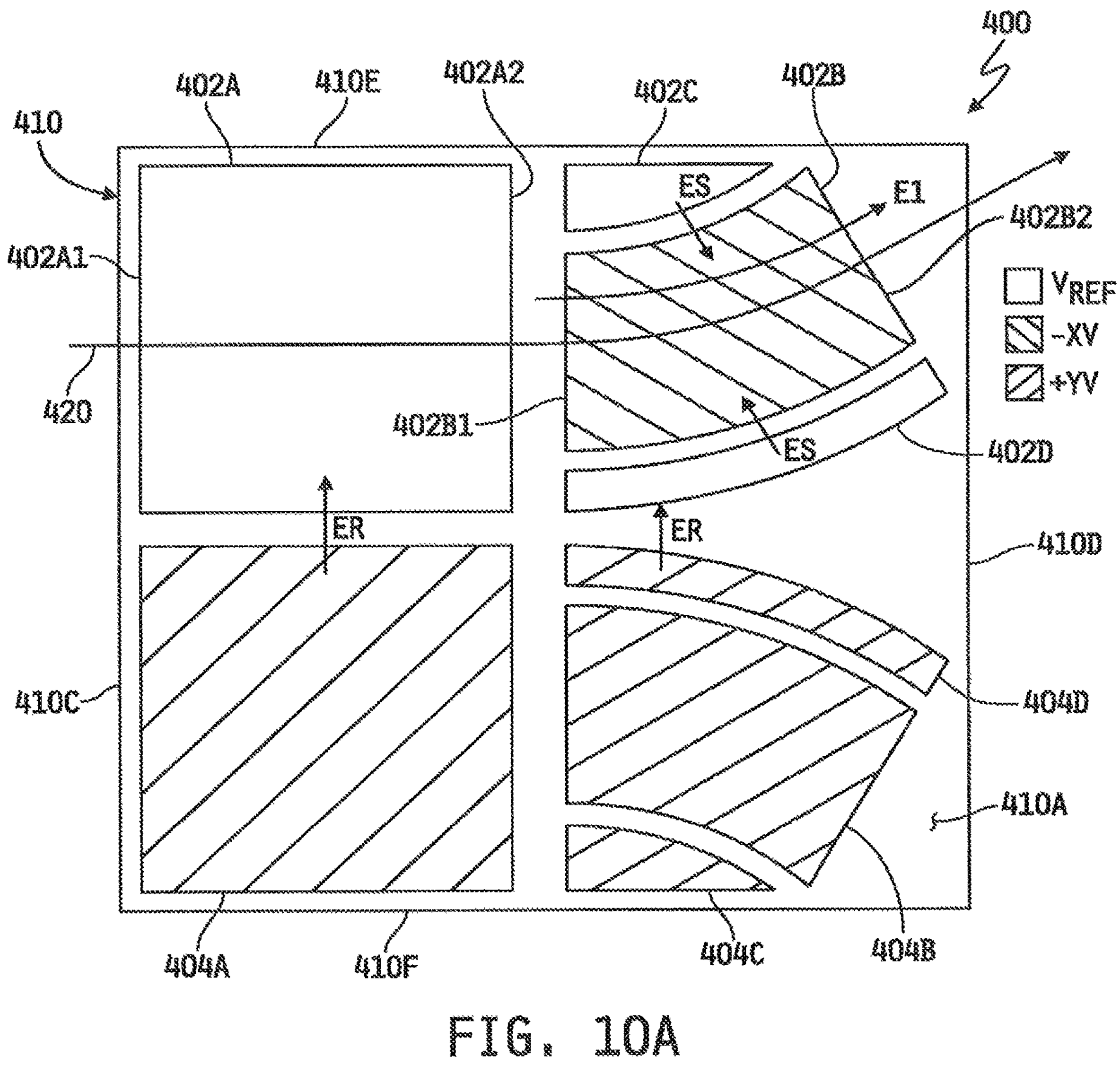

308C
300
312
302
308A
308B
310A
C
310B
310C
C
C
C
306A
ϕ1
ϕ2
RF
316
304

FIG. 8



400
410
402A
410E
402A2
402C
402B
ES
E1
402B2
402A1
V_{REF}
-XV
+YV
420
402B1
ES
402D
ER
ER
410D
404D
410C
410A
404A
410F
404C
404B

FIG. 10A

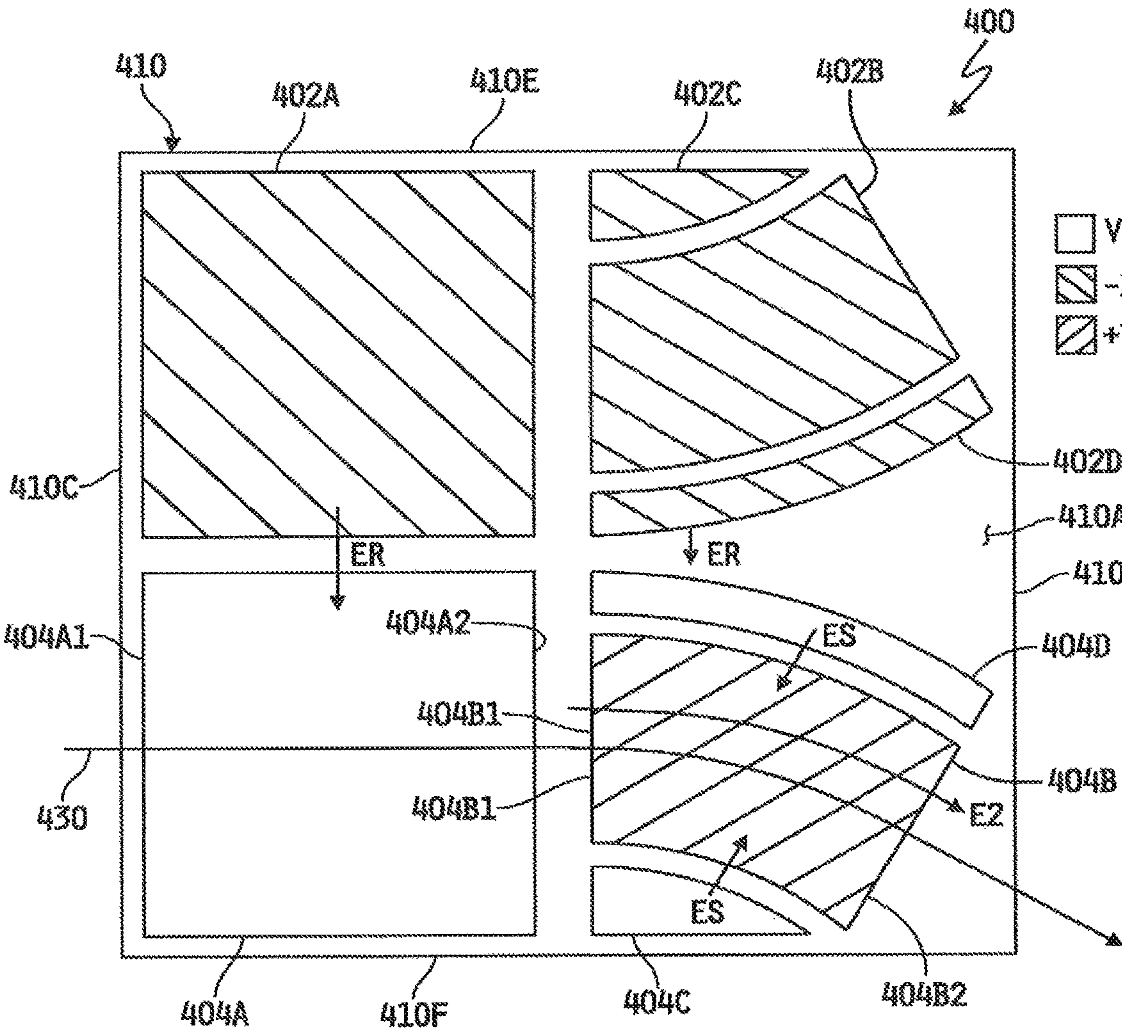

400
410
402A
410E
402C
402B
V_{REF}
-XV
+YV
410C
402D
410A
ER
ER
410D
404A1
404A2
ES
404D
404B1
404B1
404B
430
E2
ES
404A
410F
404C
404B2

FIG. 10B

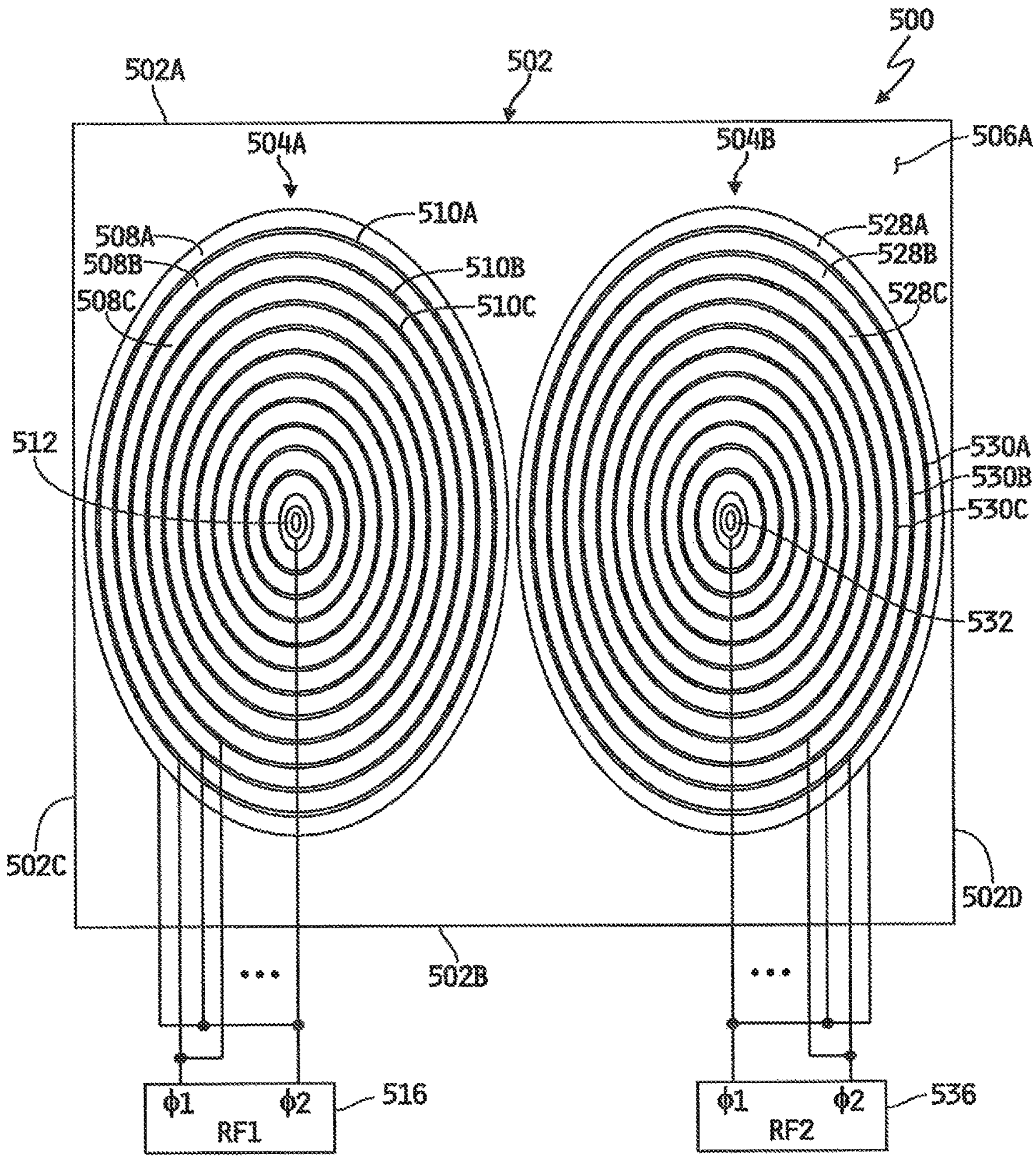

500
502A
502
504A
504B
506A
510A
508A
508B
510B
508C
510C
528A
528B
528C
512
530A
530B
530C
532
502C
502D
502B
ϕ1
ϕ2
516
RF1
ϕ1
ϕ2
536
RF2

FIG. 11

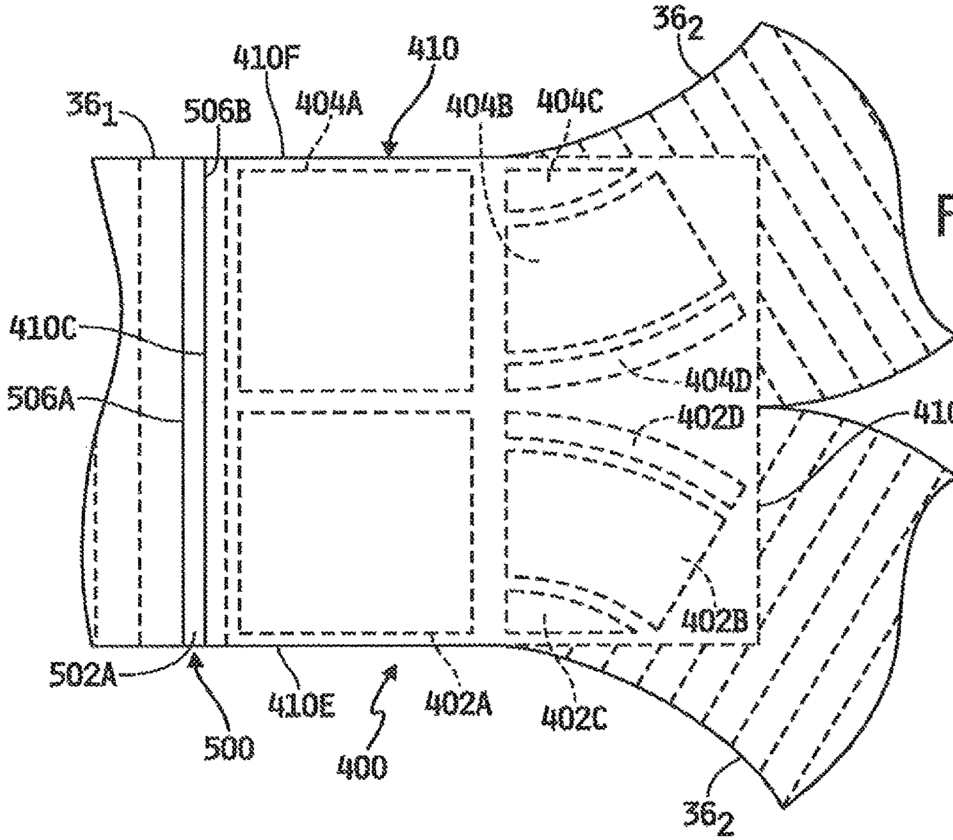


FIG. 12A

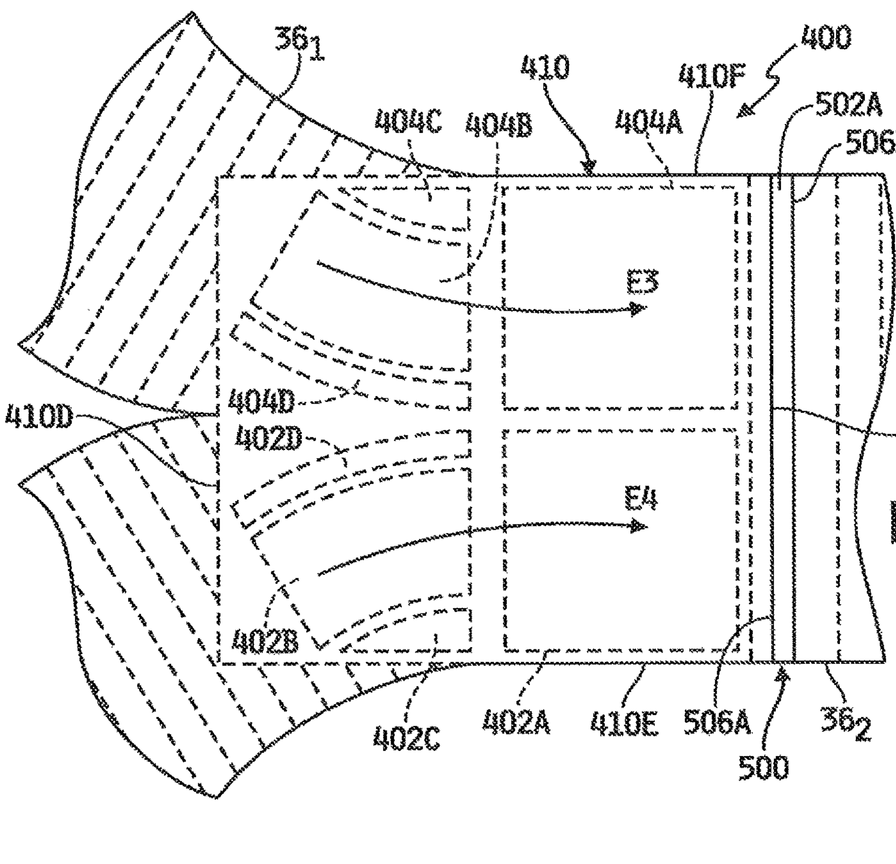


FIG. 12B

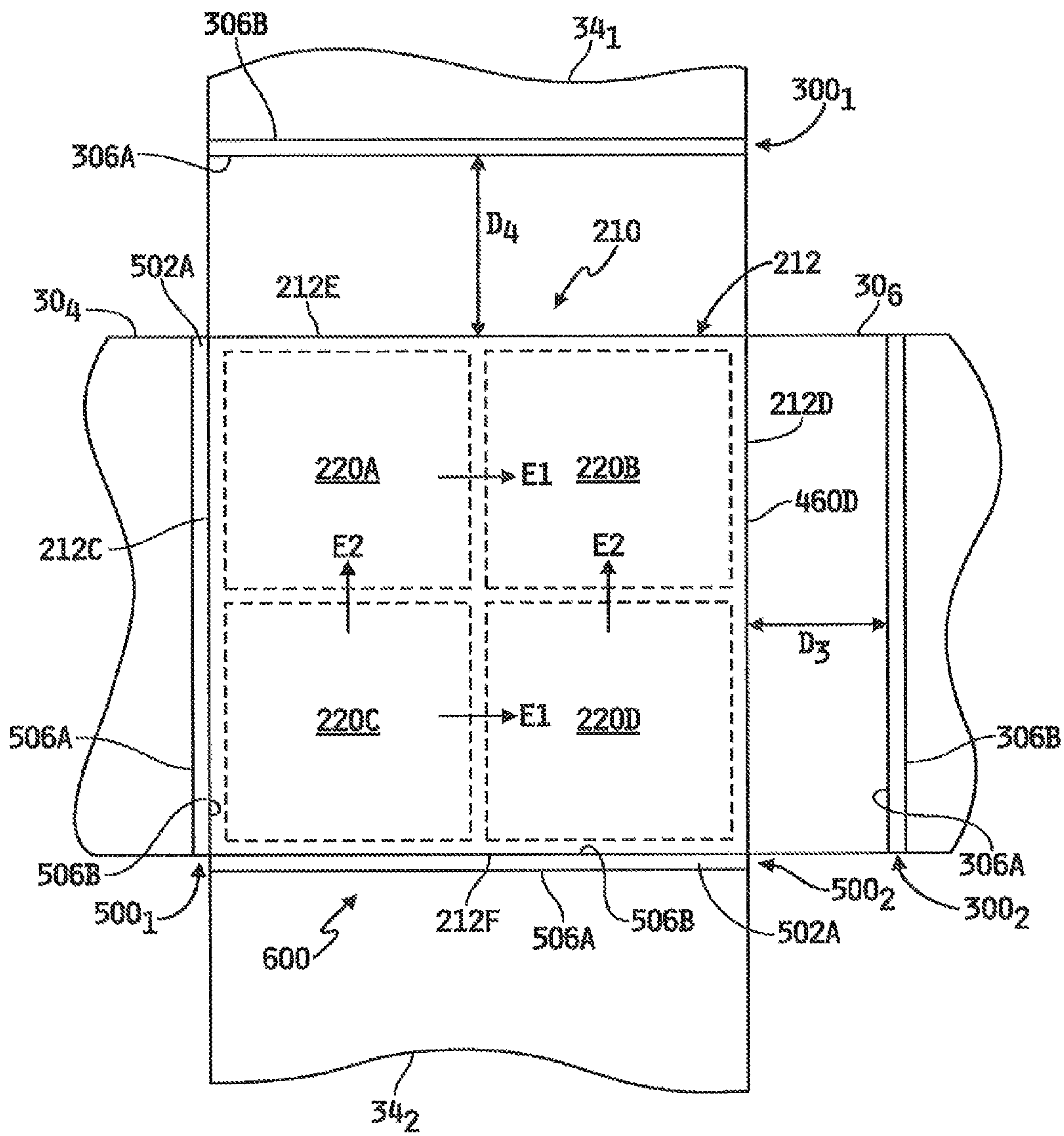

306B
34_1
300_1
306A
D_4
210
502A
212
30_4
212E
30_6
212D
220A
E1
220B
460D
212C
E2
E2
D_3
220C
E1
220D
506A
306B
306A
506B
500_2
300_2
500_1
212F
506A
506B
502A
600
34_2

FIG. 13

CLOSED PATH ION MOBILITY SPECTROMETER HAVING A COMMON ION INLET AND OUTLET

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation of U.S. patent application Ser. No. 15/606,478 filed May 26, 2017, which is a continuation-in-part of U.S. patent application Ser. No. 15/023,575, filed Mar. 21, 2016, which is a U.S. national phase of International Application No. PCT/US2014/056970, filed Sep. 23, 2014, which claims the benefit of, and priority to, U.S. Patent Application Ser. No. 61/882,891, filed Sep. 26, 2013, the disclosures of which are expressly incorporated herein by reference in their entireties.

GOVERNMENT RIGHTS

This invention was made with government support under GM090797 awarded by the National Institutes of Health. The United States Government has certain rights in the invention.

FIELD OF THE INVENTION

This disclosure relates generally to the field of spectrometry, and more specifically to instruments for separating ions in time as a function of ion mobility.

BACKGROUND

Ion mobility spectrometers are analytical instruments used to investigate properties of charged particles by separating the charged particles, i.e., ions, in time as a function of ion mobility. In the typical ion mobility spectrometers, an electric drift field is established in a drift tube filled with a buffer gas, and as the ions move through the drift tube under the influence of the electric drift field the ions collide with the buffer gas and separate as a function their collision cross-sections such that more compact conformers reach the end of the drift tube faster than less compact conformers. Known drift tubes may be so-called single-pass drift tubes, i.e., linear or non-linear drift tubes through which ions traverse only once between ion inlets and outlets thereof, or so-called multiple-pass drift tubes, i.e., linear or closed-path drift tubes through which ions may traverse multiple times before exit.

SUMMARY

The present invention may comprise one or more of the features recited in the attached claims, and/or one or more of the following features and combinations thereof. In one aspect, a hybrid ion mobility spectrometer may comprise a single-pass drift tube having an ion inlet at one end and an ion outlet at an opposite end, the single-pass drift tube configured to separate in time ions entering the ion inlet thereof and traveling therethrough according to a first function of ion mobility, a multiple-pass drift tube having an ion inlet and an ion outlet each coupled to the single pass drift tube between the ion inlet of the single-pass drift tube and the ion outlet of the single-pass drift tube, the multiple-pass drift tube configured to separate in time ions entering the ion inlet of the multiple-pass drift tube and traveling one or more times therethrough according to the first or a second function of ion mobility, and at least one ion steering channel controllable to selectively pass ions traveling through the single-pass drift tube into the multiple-pass drift tube via the ion inlet of the multiple-pass drift tube and to selectively pass ions traveling through the multiple-pass drift tube into the single-pass drift tube via the ion outlet of the multiple-pass drift tube.

In another aspect, a hybrid ion mobility spectrometer may comprise a single-pass drift tube configured to separate in time ions traveling axially therethrough in a first direction of ion travel according to a first function of ion mobility, a closed-path, multiple-pass drift tube configured to separate in time ions traveling axially therethrough one or more times in a second direction of ion travel according to the first or a second function of ion mobility, the second direction of ion travel different from the first direction of ion travel, and an ion steering channel disposed in-line with single-pass drift tube and in-line with the multiple-pass drift tube, the ion steering channel selectively controllable to steer ions traveling therein from the single-pass drift tube into the multiple-pass drift tube, the ion steering channel further selectively controllable to steer ions traveling therein from the multiple-pass drift tube into the single-pass drift tube.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a simplified diagram of an embodiment of a hybrid ion mobility spectrometer.

FIG. **1**B is a simplified diagram of an alternate embodiment of a hybrid ion mobility spectrometer,

FIG. **1**C is a simplified diagram of another alternate embodiment of a hybrid ion mobility spectrometer.

FIG. **1**D is a simplified diagram of yet another alternate embodiment of a hybrid ion mobility spectrometer.

FIG. **1**E is a simplified diagram of the embodiment illustrated in FIG. **1**D viewed orthogonally from the view illustrated in FIG. **1**D.

FIG. **1**F is a simplified diagram of an embodiment of the transition region of the hybrid ion mobility spectrometer illustrated in FIGS. **1**D and **1**E.

FIG. **2** is a simplified diagram of an embodiment of a drift tube segment that may be used in any of the hybrid ion mobility spectrometers of FIGS. **1**A-**1**C.

FIG. **3** includes FIGS. **3**A and **3**B and is a simplified flowchart of an embodiment of a process for separating ions using any of the hybrid ion mobility spectrometers of FIGS. **1**A-**1**F.

FIG. **4**A is a simplified diagram of another embodiment of the transition region of the hybrid ion mobility spectrometer illustrated in FIGS. **1**D and **1**E.

FIG. **4**B is a simplified diagram of still another embodiment of the transition region of the hybrid ion mobility spectrometer illustrated in FIGS. **1**D and **1**E.

FIG. **5** is a bottom plan view of one of the planar members of either of the embodiments illustrated in FIGS. **4**A and **4**B.

FIG. **6** is a simplified perspective view of an embodiment of an ion steering channel that may be implemented in any of the hybrid ion mobility spectrometers illustrated in FIGS. **1**A-**1**F.

FIG. **7**A is a simplified perspective diagram illustrating an example operating mode of the ion steering channel illustrated in FIG. **6**.

FIG. **7**B is a simplified perspective diagram illustrating another example operating mode of the ion steering channel illustrated in FIG. **6**.

FIG. **8** is a simplified elevational diagram illustrating an embodiment of an ion carpet that may be implemented in any of the hybrid ion mobility spectrometers illustrated in FIGS. **1**A-**1**F.

FIG. **9** is a simplified elevational diagram illustrating an embodiment of one of two planar members forming another embodiment of an ion steering channel that may be implemented in any of the hybrid ion mobility spectrometers illustrated in FIGS. **1**A-**1**F.

FIG. **10**A is a simplified elevational diagram illustrating an example operating mode of the ion steering channel partially illustrated in FIG. **9**.

FIG. **10**B is a simplified perspective diagram illustrating another example operating mode of the ion steering channel partially illustrated in FIG. **9**.

FIG. **11** is a simplified elevational diagram illustrating another embodiment of an ion carpet that may be implemented in any of the hybrid ion mobility spectrometers illustrated in FIGS. **1**A-**1**F.

FIG. **12**A is a simplified plan diagram illustrating an example combination the ion steering channel partially illustrated in FIG. **9** and the ion carpet illustrated in FIG. **11**, illustratively implemented in either of the hybrid ion mobility spectrometers illustrated in FIGS. **1**A and **1**B.

FIG. **12**B is a simplified plan diagram illustrating another example combination the ion steering channel partially illustrated in FIG. **9** and the ion carpet illustrated in FIG. **11**, illustratively implemented in the hybrid ion mobility spectrometer illustrated in FIG. **1**A.

FIG. **13** is a simplified plan diagram illustrating an example combination the ion steering channel illustrated in FIG. **6**, two of the ion carpets illustrated in FIG. **8** and two of the ion carpets illustrated in FIG. **11**, illustratively implemented in the hybrid ion mobility spectrometer illustrated in FIGS. **1**D and **1**E.

DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS

For the purposes of promoting an understanding of the principles of the invention, reference will now be made to a number of illustrative embodiments shown in the attached drawing and specific language will be used to describe the same.

Referring to FIG. **1**A, a simplified diagram of an embodiment of a hybrid mobility spectrometer **10** is shown. The hybrid ion mobility spectrometer **10** illustratively includes a single-pass drift tube **12** through which ions can be separated in time according to a first function of ion mobility, and a multiple-pass drift tube **14**, coupled to the single-pass drift tube **12** between an ion inlet **16** and an ion outlet **20** of the single-pass drift tube **12**, through which ions can be separated in time according to a second function of ion mobility. The spectrometer **10** further illustratively includes a set of ion gates, e.g., G**1**-G**3**, each of which are controllable between open and closed positions, and the set of ion gates is illustratively controlled such that some or all of the ions traveling through the single-pass drift tube **12** may be selectively passed into the multiple-pass drift tube **14** via an ion inlet $\mathbf{36}_1$ of the multiple-pass drift tube **14**, and some or all of the ions traveling through the multiple-pass drift tube **14** may be selectively passed back into the single-pass drift tube **12** via an ion outlet $\mathbf{36}_2$ of the multiple-pass drift tube **14**, and the ions then exit the single-pass drift tube **12** via the ion outlet **20** thereof. In the embodiment illustrated in FIG. **1**A, an ion source **18** is coupled to the ion inlet **16** of the single-pass drift tube **12**, and an ion detector **22** is positioned to receive ions exiting the ion outlet **20** of the single-pass drift tube **12**.

The foregoing configuration of the ion mobility spectrometer **10** provides for the ability to pass all or a subset of ions in the single-pass drift tube **12** to the multiple-pass drift tube **14** for additional and/or alternate separation before the ions exit the outlet **20** of the single-pass drift tube **12**. Advantageously, because both drift tubes **12**, **14** operate on ions generated from a single ion source **18** coupled to the ion inlet **16** of the single-pass drift tube **12**, such additional and/or alternate separation may thus be carried out using ions from the same sample. In one specific operational mode of the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A, for example, the set of ion gates, e.g., ion gates G**1**-G**3**, may be controlled such that ions generated by the ion source **18** are first confined to the single-pass drift tube **12**, and electric fields within the single-pass drift tube **12** are controlled such that ions generated at the ion source **18** travel, i.e., drift, through only the single-pass drift tube **12** where they separate in time as a first function of ion mobility defined by the various structural dimensions and operating parameters of the single-pass drift tube **12**. The resulting ion spectral information is then analyzed and if, for example, it is discovered that in the ion spectral information a subset, e.g., two or more, of ion intensity peaks in an ion mobility range of interest, e.g., in a particular range of drift times, are crowded together and cannot be satisfactorily resolved over the length of the single-pass drift tube **12**, ions are then generated a second time, or are continuously generated without interruption, and the set of ion gates, e.g., ion gates G**1**-G**3**, is controlled in one embodiment to pass or divert ions traveling through the single-pass drift tube **12** that are within the ion mobility range of interest into the multiple-pass drift tube **14**. The set of ion gates, e.g., ion gates G**1**-G**3**, is then controlled to confine the diverted ions within the multiple-pass drift tube **14** and electric fields within the multiple-pass drift tube **14** are controlled such that the diverted ions pass, i.e., drift, one or more times through, i.e., about, the multiple-pass drift tube **14** and separate in time according to a second function of ion mobility, which may or may not be the same as the first function of ion mobility, and which is defined by the structure and operating parameters of the multiple-pass drift tube **14**, and the set of ion gates, e.g., ion gates G**1**-G**3** may then be controlled to pass or divert some or all of the ions traveling through the multiple-pass drift tube **14** back into the single-pass drift tube **12** where they are then directed to the ion outlet **20** of the single-pass drift tube. In one alternate embodiment, the set of ion gates, e.g., ion gates G**1**-G**3**, may be controlled to pass or divert ions some or all of the ions traveling through the single-pass drift tube **12** into the multiple-pass drift tube **14**, and the electric fields within the multiple-pass drift tube **14**, along with the set of ion gates, e.g., ion gates G**1**-G**3**, may then controlled in a known manner to confine the diverted ions within the multiple-pass drift tube **14** so that the ions separate in time according to a second function of ion mobility in which only the diverted ions within the ion mobility range of interest pass one or more times through, i.e., about, the multiple-pass drift tube **14**. The set of ion gates, e.g., ion gates G**1**-G**3** may then be controlled to pass or divert some or all of the ions traveling through the multiple-pass drift tube **14** back into the single-pass drift tube **12** where they are then directed to the ion outlet **20** of the single-pass drift tube. In another alternate embodiment, the set of ion gates, e.g., ion gates G**1**-G**3**, may be controlled to pass or divert some or all of the ions traveling through the single-pass drift tube **12** into the multiple-pass drift tube **14**, and the electric fields within the multiple-pass drift tube **14**, along with the set of ion gates, e.g., ion gates G**1**-G**3**, may then controlled in a known manner to confine the diverted ions within the multiple-pass drift tube **14** so that the ions separate in time according to a second function of ion mobility, which may or may not be the same as the first function of ion mobility, and which is defined by the structure and operating parameters of the multiple-pass drift tube **14**. The ion gates, e.g., ion gates G**1**-G**3**, may then be controlled to pass or divert some or all of the ions traveling through the multiple-pass drift tube **14** back into the single-pass drift tube **12**, and one or more ion gates positioned within the drift tube section D**2** may be controlled to pass through the ion outlet **20** only ions within the ion mobility range of interest.

In some embodiments, one or more of the ion gates in the set of ion gates, e.g., G**1**-G**3**, may be controlled to one or more intermediate positions between the open and closed positions. In such embodiments, and according to another specific operating mode of the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A, for example, the set of ion gates, e.g., ion gates G**1**-G**3**, may be controlled to direct some of the ions traveling through the single-pass drift **12** into the multiple-pass drift tube **14** while also allowing others of the ions traveling through the single-pass drift tube **12** to travel completely through the single-pass drift tube **12**, e.g., to and through the outlet **20** thereof. In such an operating mode, ions supplied by the single or common ion source **18** to the inlet **16** of the single-pass drift tube **12** thus travel in parallel through the single-pass drift tube **12** and the combination of the single-pass drift tube **12** and the multiple-pass drift tube **14**, with some of the ions traveling directly through the single-pass drift tube **12** to and through the ion outlet **20** and others of the ions traveling through the single-pass drift tube **12**, to and through the multiple-pass drift tube **14**, then back to and through any remaining section(s) of the single-pass drift tube **12** and exiting the ion outlet **20** of the single-pass drift tube **12**.

In any case, further details relating to various structural embodiments of the hybrid ion mobility spectrometer briefly described above and the foregoing operation thereof are described below and/or illustrated in the attached drawings, although it will be understood that other structural embodiments and operational modes of the hybrid ion mobility spectrometer illustrated and described herein will occur to those skilled in the art and that such other structural embodiments and operational modes are contemplated by this disclosure.

Referring now specifically to FIG. **1**A, an embodiment of the hybrid ion mobility spectrometer **10** briefly described above is shown. As described above, the hybrid ion mobility spectrometer **10** includes an ion source **18** coupled to an ion inlet **16** defined at one end of a single-pass ion mobility spectrometer **12**, and an ion outlet **20** is defined at an opposite end of the single-pass ion mobility spectrometer **12**. A multiple-pass ion mobility spectrometer **14** is coupled to the single-pass ion mobility spectrometer **12** between the ion inlet **16** and the ion outlet **20** thereof such that ions may be selectively passed from the single-pass ion mobility spectrometer **12** to the multiple-pass ion mobility spectrometer **14** and vice versa. For purposes of this disclosure, the term "single-pass ion mobility spectrometer" means an ion mobility spectrometer, or portion thereof, through which ions pass a single time, and the term "multiple-pass ion mobility spectrometer" means an ion mobility spectrometer, or portion thereof, through which ions may pass multiple times. Neither such ion mobility spectrometer is limited to any particular shape or configuration, and the single-pass ion mobility spectrometer **12** and/or the multiple-pass ion mobility spectrometer **14** may be or include a linear, piece-wise-linear and/or non-linear drift tube.

In the illustrated embodiment, the ion outlet **20** of the single-pass ion mobility spectrometer **12** is coupled to an ion detector **22** which is configured to detect, in a conventional manner, ions exiting the ion outlet **20** of the single-pass ion mobility spectrometer **12**. In alternate embodiments, one or more additional ion separation and/or ion analyzing apparatuses may be positioned between the ion outlet **20** of the single-pass ion mobility spectrometer **12** and the ion detector **22**, and in any such alternate embodiment one or more ion detectors **22** may be coupled to or integral with any of the additional ion separation and/or ion analyzing apparatuses, alternatively to or in addition to the single-pass ion mobility spectrometer **12**.

The ion source **18** may be any conventional ion source, examples of which include, but are not limited to, an electrospray ion source, a matrix-assisted laser desorption ion source (MALDI), or the like. Alternatively or additionally, the ion source **18** may include one or more conventional apparatuses to collect all or a subset of the generated ions (i.e., within a defined range of ion mobilities and/or within a defined range of ion mass-to-charge ratios) and/or to structurally modify, e.g., fragment and/or change the conformations of, some or all of the generated ions and/or to normalize or otherwise modify the charge states of one or more of the generated ions. Alternatively or additionally still, the ion source **18** may be or include one or more known apparatuses that separate ions and/or one or more isotopes thereof as a function of any molecular characteristic, e.g., ion mass-to-charge ratio, ion mobility, ion retention time, or the like.

In the embodiment illustrated in FIG. **1**A, the single-pass ion mobility spectrometer **12** is made up of three cascaded drift tube sections; a first drift tube section D**1** coupled to the ion source **18**, a transition drift tube section DT coupled to the first drift tube section D**1** and to the drift tube of the multiple-pass ion mobility spectrometer **14**, and a second drift tube section D**2** coupled to the transition drift tube section DT and, in the illustrated embodiment, to the ion detector **22**. In one embodiment, the first drift tube section D**1** is illustratively a linear drift tube section and includes a cascaded arrangement of any number, N, of conventional linear drift tube sub-sections $\mathbf{30}_N$ (three such drift tube sub-sections $\mathbf{30}_1$, $\mathbf{30}_2$ and $\mathbf{30}_3$ shown) and any number, M, of conventional linear drift tube funnels $\mathbf{32}_M$ (two such drift tube funnels $\mathbf{32}_1$ and $\mathbf{32}_2$ shown), wherein a different drift tube funnel **32** may be interposed between any number of cascaded drift tube sub-sections **30**. The second drift tube section D**2** is likewise illustratively a linear drift tube section and may likewise include a cascaded arrangement of any number, Q, of conventional drift tube sections $\mathbf{30}_Q$ (two such drift tube sub-sections $\mathbf{30}_4$ and $\mathbf{30}_5$ shown) and any number, R, of conventional drift tube funnels $\mathbf{32}_R$ (two such drift tube funnels $\mathbf{32}_9$ and $\mathbf{32}_{10}$ shown), wherein a different drift tube funnel **32** may be interposed between any number of cascaded drift tube sub-sections **30**. Alternatively, the second drift tube section D**2** may include only a single drift tube sub-section **30** or drift tube funnel **32** which is coupled at one end to the transition drift tube section DT and defines the ion outlet **20** of the single-pass ion mobility spectrometer **12** at its opposite end. Alternatively still, the second drift tube section D**2** may be omitted altogether and the ion outlet of the transition drift tube section DT may define the ion outlet **20** of the single-pass ion mobility spectrometer **12**.

The drift tube sub-sections **30** and the drift tube funnels **32** illustrated in FIG. **1**A are illustratively linear components in that each drift tube sub-section **30** and each drift tube funnel **32** defines a linear ion drift tube axis therethrough between an ion inlet and ion outlet thereof. The resulting drift tube sections D**1** and D**2** shown in FIG. **1**A therefore likewise linear drift tube sections, it will be understood that either or both of the drift tube sections D**1** and D**2** may alternatively be piecewise linear or non-linear, or include one or more piecewise linear or non-linear subsections.

In any case, the one or more drift tube funnels **32** are illustratively controlled in a conventional manner to radially focus ions inwardly toward a central ion drift axis defined through the drift tube funnel **32** from an ion inlet to an ion outlet thereof. Additionally, one or more of the ion funnels **32** and/or one or more of the drift tube sub-sections **30** may include one or more ion gates controllable in a conventional manner to selectively pass ions therethrough or block ions from passing therethrough. Alternatively or additionally, one or more of the ion funnels **32** may include one or more regions that is/are controllable in a conventional manner to modify the structures of some or all of the ions passing therethrough, e.g., via ion fragmentation and/or inducing conformational changes in the ions. Further details relating to illustrative embodiments of the drift tube sub-sections **30** and the drift tube funnels **32** shown in FIG. **1**A and described above are described in U.S. Patent Pub. No. 2007/0114382 A1 and also in related U.S. Pat. No. 8,618,475, the disclosures of which are incorporated herein by reference.

The transition drift tube section DT in the embodiment illustrated in FIG. **1**A, is illustratively made up of a number, S, of curved drift tube sub-sections $\mathbf{34}_S$ (two such curved drift tube sub-sections $\mathbf{34}_1$ and $\mathbf{34}_2$ shown, with the curved drift tube sub-section $\mathbf{34}_1$ defining an ion inlet to the transition drift tube section DT and coupled to the ion outlet of the first drift tube section D**1**, and with the curved drift tube sub-section $\mathbf{34}_2$ defining an ion outlet of the transition drift tube section DT and coupled to the ion inlet of the second drift tube section D**2**), a number, T, of the drift tube funnels $\mathbf{32}_T$ (three such drift tube funnels $\mathbf{32}_3$, $\mathbf{32}_4$ and $\mathbf{32}_5$ shown) and sub-sections of each of two curved, Y-shaped drift tube sections $\mathbf{36}_1$ and $\mathbf{36}_2$. The multiple-pass ion mobility spectrometer **14**, in the embodiment illustrated in FIG. **1**A, is illustratively provided in the form of a closed-path drift tube made up of a number, U, of the curved drift tube sub-sections $\mathbf{34}_U$ (two such curved drift tube sub-sections $\mathbf{34}_3$ and $\mathbf{34}_4$ shown), remaining sub-sections of the two curved, Y-shaped drift tube sections $\mathbf{36}_1$ and $\mathbf{36}_2$, and a number, V, of the drift tube funnels $\mathbf{32}_V$ (four such drift tube funnels $\mathbf{32}_5$, $\mathbf{32}_6$, $\mathbf{32}_7$ and $\mathbf{32}_8$ shown). It will be understood, however, that the multiple-pass drift tube **14** may alternatively not form a closed path but may nevertheless be configured to pass ions multiple times therethrough.

In the embodiment illustrated in FIG. **1**A, the sub-section or branch of the curved, Y-shaped drift tube section $\mathbf{36}_1$ that is coupled to the drift tube funnel $\mathbf{32}_3$ serves the dual function as part of the single-pass ion mobility spectrometer **12** and also as an ion inlet to the multiple-pass ion mobility spectrometer **14**, and the sub-section or branch of the curved, Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_4$ likewise serves the dual function as part of the single-pass ion mobility spectrometer **12** and also as an ion outlet of the multiple-pass ion mobility spectrometer **14**. The drift tube funnel $\mathbf{32}_5$ is illustratively shared by the single-pass ion mobility spectrometer **12** and the multiple-pass ion mobility spectrometer **14** and therefore forms part of each. Further details relating to illustrative embodiments of the curved drift tube sub-sections **34**, the curved Y-shaped drift tube sections **36** and the closed-path configuration of the multiple-pass ion mobility spectrometer **14** shown in FIG. **1**A and described above are described in U.S. Pat. No. 8,362,420, the disclosure of which is incorporated herein by reference.

The hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A includes three ion gates, G**1**-G**3**, each of which is controllable in a conventional manner to selectively allow ions to pass therethrough and to selectively block ions from passing therethrough. In one embodiment, the ion gates G**1**-G**3** are each provided in the form of a mesh or grid, and a DC potential applied thereto, or a DC differential applied between a mesh or grid and an adjacent ring, is controlled such that at one DC level or DC differential value ions pass through the ion gate and at a different DC level or DC differential value ions are blocked from passing through the ion gate. In alternate embodiments, the ion gate function of one or more of the ion gates G**1**-G**3** may be accomplished by selectively applying and varying the frequency and/or amplitude of an RF voltage to a non-meshed or gridded ring, in a conventional manner, to selectively allow passage or block passage of ions therethrough. In some embodiments, one or more of the gates G**1**-G**3** may be controlled with intermediate DC potentials and/or RF frequencies/amplitudes to pass therethrough only a portion of ions presented thereat, e.g., to allow passage through one or more of the ion gates G**1**-G**3** of only a percentage of ions that is less than 100% of the total number of ions traveling toward the one or more ion gates G**1**-G**3**. In any case, the three ion gates G**1**-G**3** are controllable, as will be described in detail below, to confine ions within the single-pass drift tube **12**, to confine ions within the multiple-pass drift tube **14**, to pass or divert at least some of the ions in the single-pass drift tube **12** into the multiple-pass drift tube **14** and/or to pass or divert at least some of the ions in the multiple-pass drift tube **14** back into the single-pass drift tube **12**.

In the embodiment illustrated in FIG. **1**A, a first one of the ion gates, G**1**, is illustratively positioned in the curved, Y-shaped drift tube section $\mathbf{36}_2$ at an interface of the sub-section of the Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_5$ and the sub-section or branch of the Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_8$. A second one of the ion gates, G**2**, is illustratively positioned in the curved, Y-shaped drift tube section $\mathbf{36}_2$ at an interface of the sub-section of the Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_5$ and the sub-section or branch of the Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_4$. A third one of the ion gate, G**3**, is illustratively positioned in the curved, Y-shaped drift tube section $\mathbf{36}_1$ at an interface of the sub-section of the Y-shaped drift tube section $\mathbf{36}_1$ that is coupled to the drift tube funnel $\mathbf{32}_5$ and the sub-section or branch of the Y-shaped drift tube section $\mathbf{36}_1$ that is coupled to the drift tube funnel $\mathbf{32}_3$. It will be understood that the hybrid ion mobility spectrometer **10** may include more or fewer such ion gates, and that any such alternative embodiment of the hybrid ion mobility spectrometer is contemplated by this disclosure.

In one alternate embodiment of the hybrid ion mobility spectrometer **10**, one or more of the drift tube sub-sections **30**, **34**, **36** and/or one or more of the drift tube funnels **32** may be provided in the form of a two-part sub-section or funnel defining a first drift tube region having an ion inlet defining the ion inlet of the sub-section or funnel and an ion outlet coupled to an ion inlet of an ion elimination region having an ion outlet defining the ion outlet of the sub-section or funnel. Further details relating to the structure and various operational modes of such alternately configured drift tube sub-sections and/or funnels are described in co-pending U.S. Patent Application Pub. No. 2013/0292562, the disclosure of which is incorporated herein by reference.

In another alternate embodiment of the hybrid ion mobility spectrometer **10**, one or more of the drift tube funnels **32** and/or one or more of the drift tube sub-sections **30**, **34**, **36** may be provided in the form of a conventional drift tube sub-section **30** to which RF voltages may be applied to radially focus ions inwardly toward the ion drift path defined therethrough. One illustrative embodiment of such a drift tube sub-section **50** is shown in FIG. **2**, and includes a series of identically-dimensioned, electrically insulating rings **56** each separating adjacent ones of a series of identically-dimensioned, electrically conductive rings **58**, with all such rings **56**, **58** stacked and clamped together between an ion inlet **52** and an ion outlet **54** of the drift tube sub-section **50**. Illustratively, the last several, e.g., two, electrically insulating rings may be (but need not be) provided in the form of reduced-thickness rings **60** (e.g., approximately ½ of the thickness of the rings **56**), the purpose which will be described below.

In the illustrated embodiment, an RF voltage source **70** produces two RF voltages, ϕ_1 and ϕ_2 each 180 degrees out of phase with respect to the other, with ϕ_1 applied via a separate capacitor, C**1**, to all odd (or even) numbered rings **58** and ϕ_2 applied via a separate capacitor, C**1**, to all even (or odd) numbered rings **58** such that ϕ_1 and ϕ_2 are applied alternately to the series of rings **58** in the stack. A DC potential is applied via series-connected resistors, R, to the rings **58** to create a substantially uniform electric drift field in the drift tube sub-section **50**, and ions drift through the drift tube sub-section **50** under the influence of the electric drift field. The frequencies and/or amplitudes of the RF voltages ϕ_1 and ϕ_2 are illustratively selected in a conventional manner to radially focus ions drifting through the drift tube sub-section **50** toward an ion drift axis defined centrally through the drift tube sub-section **50**. In embodiments in which the reduced-width, electrically insulating rings **60** are included, another RF voltage source **72** may be provided to produce an RF voltage ϕ_3 that is applied through a different capacitor, C**2**, to each of the electrically conductive rings **58** contacting one of the rings **60**. The frequency and/or amplitude of ϕ_3 is controlled in a conventional manner to selectively allow passage of ions through the electrically conductive rings **58** connected to ϕ_3 or block passage of ions therethrough to thereby provide an ion gating function.

The drift tube sub-sections **50** with the radial ion focusing feature described above may be used in place of one or more of the drift tube funnels **32** and/or in place of one or more of the drift tube sub-sections **30**, **34**, **36** illustrated in FIG. **1**A. Alternatively or additionally, the drift tube sub-sections **50** with or without the radial ion focusing feature but with the ion gating feature described above may be used in place of one or more of the ion gates G**1**-G**3** illustrated in FIG. **1**A. In any of the embodiments illustrated in the attached figures and described herein, either or both of the single-pass drift tube and the multiple-pass drift tube may be operated in a conventional traveling wave operating mode, i.e., one in which one or more oscillating, i.e., AC, electric fields are established within the various drift tube sections to cause the ions to separate as they drift through the respective drift tube.

Referring again to FIG. **1**A, a number of voltage sources **40** are electrically connected to various parts of the hybrid ion mobility spectrometer **10**, and the number of voltage sources **40** are selected and controlled to apply appropriate DC and/or AC voltages to the various parts and components of the hybrid ion mobility spectrometer **10** for operation thereof. For example, one or more of the voltage sources **40** is/are electrically connected to the ion source **18** to control the ion source **18** in a conventional manner to generate, collect and/or process ions as described above. One or more others of the voltage sources **40** is/are electrically connected to each drift tube sub-section **30**, **34**, **36** and each drift tube funnel **32** to establish an electric drift field therein through which ions traverse the single-pass drift tube **12** and the multiple-pass drift tube **14**. One or more others of the voltage sources **40** is/are electrically connected to the drift tube funnels **32** to radially focus ions inwardly toward the drift tube axis defined therethrough, and/or to control operation of one or more ion gates contained therein to pass or block ions, and/or to control one or more ion activation regions included in one or more of the funnels **32** to modify the structure of ions passing therethrough, e.g., via ion fragmentation and/or by inducing conformational changes in ions without fragmenting them. One or more others of the voltage sources **40** is/are electrically connected to each of the ion gates G**1**-G**3** and selectively controlled to pass or block ions as described above and as will be described in greater detail below with respect to the process illustrated in FIG. **3**. In any case, the one or more voltage sources **40** are conventional and may be individually programmed for operation or controlled by a processor **42** (e.g., amplitude, frequency, timing of activation and/or deactivation, etc.) as shown by dashed-line representation. The processor **42** is, in any event, electrically connected to the ion detector, and the processor **42** includes a memory having instructions stored therein that are executable by the processor **42** to process ion detection signals produced by the ion detector **22** and produce corresponding ion mobility spectral information, e.g., as a function of ion drift time through the single-pass drift tube **12** and/or the multiple-pass drift tube **14**.

A gas source **44**, e.g., single buffer gas, combination of gases to form a buffer gas, one or a combination of other gases, etc., is fluidly coupled to the hybrid ion mobility spectrometer **10** via a fluid conduit **46**. In embodiments of the hybrid ion mobility spectrometer **10** constructed from open-ended sub-sections **30**, **34**, **36** and with or without open-ended drift tube funnels **32**, the resulting spectrometer **10** is a continuous cavity spectrometer, and the single gas source **44** may thus be used to fill the entire spectrometer **10**, including the single-pass drift tube **12** and the multiple-pass drift tube **14**. In alternative embodiments, two or more gas sources may be used, and the hybrid ion mobility spectrometer **10** may be partitioned in a conventional manner to confine the two or more gases to corresponding portions of the spectrometer **10**. The gas source **44** may be manually controlled, programmable for automatic control and/or controlled by the processor **42** as shown by dashed-line representation in FIG. **1**A.

Referring now to FIG. **1**B, an alternate embodiment of a hybrid ion mobility spectrometer **10'** is shown. The hybrid ion mobility spectrometer **10'** is identical in many respects to the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A and described above. Like features are identified by like reference numbers, and a detailed description of common features between the two spectrometers **10** and **10'** will not be repeated here for brevity. It will be further understood that the various embodiments of the various components and aspects to the hybrid ion mobility spectrometer **10** described above apply equally to the hybrid ion mobility spectrometer **10'**.

The hybrid ion mobility spectrometer **10'** illustrated in FIG. **1**B differs from the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A primarily in the construction of the single-pass drift tube **12'** and in the number and location of the various ion gates that are controlled to achieve operation of the spectrometer **10** as described above. In the embodiment illustrated in FIG. **1**B, for example, the drift tube funnel $\mathbf{32}_3$ is coupled at its ion inlet to one ion outlet branch of a Y-shaped drift tube sub-section $\mathbf{38}_1$ having another ion outlet branch coupled to an ion inlet of another drift tube funnel $\mathbf{32}_{11}$, wherein both such ion outlet branches are coupled to a common ion inlet branch having an ion inlet coupled to an ion outlet of the drift tube funnel $\mathbf{32}_2$. The drift tube funnel $\mathbf{32}_4$ is similarly coupled at its ion outlet to one ion inlet branch of another Y-shaped drift tube sub-section $\mathbf{38}_2$ having another ion inlet branch coupled to an ion outlet of the drift tube funnel $\mathbf{32}_{11}$, wherein both such ion outlet branches are coupled to a common ion outlet branch having an ion outlet coupled to an ion outlet of the drift tube funnel $\mathbf{32}_9$. In this embodiment, the single-pass drift tube **12'** is a linear drift tube made up of the linear drift tube segments D**1** and D**2** joined by a linear drift tube segment D**3** made up of the linear branches of the Y-shaped drift tube sub-sections $\mathbf{38}_1$, $\mathbf{38}_2$ and the drift tube funnel $\mathbf{32}_{11}$.

The embodiment illustrated in FIG. **1**B includes four ion gates G**1**-G**4** which are controllable, as will be described in detail below, to confine ions within the single-pass drift tube **12'**, to confine ions within the multiple-pass drift tube **14**, to pass or divert at least some of the ions in the single-pass drift tube **12'** into the multiple-pass drift tube **14** and/or to pass or divert at least some of the ions in the multiple-pass drift tube **14** back into the single-pass drift tube **12'**. A first one of the ion gates, G**1**, is illustratively positioned in the Y-shaped drift tube section $\mathbf{38}_1$ at an interface of the curved branch of the Y-shaped drift tube section $\mathbf{38}_1$ that is coupled to the drift tube funnel $\mathbf{32}_1$ and the branch of the Y-shaped drift tube section $\mathbf{38}_1$ that is coupled to the drift tube funnel $\mathbf{32}_2$. A second one of the ion gates, G**2**, is illustratively positioned in the Y-shaped drift tube section $\mathbf{38}_1$ at an interface of the linear branch of the Y-shaped drift tube section $\mathbf{38}_1$ that is coupled to the drift tube funnel $\mathbf{32}_{11}$ and the branch of the Y-shaped drift tube section $\mathbf{38}_1$ that is coupled to the drift tube funnel $\mathbf{32}_2$. A third one of the ion gates, G**3**, is illustratively positioned in the curved, Y-shaped drift tube section $\mathbf{36}_2$ at an interface of the sub-section of the Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_5$ and the sub-section or branch of the Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_8$. A fourth one of the ion gates, G**4**, is illustratively positioned in the curved, Y-shaped drift tube section $\mathbf{36}_2$ at an interface of the sub-section of the Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_5$ and the sub-section or branch of the Y-shaped drift tube section $\mathbf{36}_2$ that is coupled to the drift tube funnel $\mathbf{32}_4$. It will be understood that the hybrid ion mobility spectrometer **10'** may include more or fewer such ion gates, and that any such alternative embodiment of the hybrid ion mobility spectrometer is contemplated by this disclosure.

Referring now to FIG. **1**C, another alternate embodiment of a hybrid ion mobility spectrometer **10"** is shown. The hybrid ion mobility spectrometer **10"** is also identical in many respects to the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A and described above. Like features are identified by like reference numbers, and a detailed description of common features between the two spectrometers **10** and **10"** will not be repeated here for brevity. It will be further understood that the various embodiments of the various components and aspects to the hybrid ion mobility spectrometer **10** described above apply equally to the hybrid ion mobility spectrometer **10"**.

The hybrid ion mobility spectrometer **10"** illustrated in FIG. **1**C differs from the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A primarily in the construction of each of the single-pass drift tube **12"** and the multiple-pass drift tube **14'**, and also in the location of the various ion gates that are controlled to achieve operation of the spectrometer **10** as described above. In the embodiment illustrated in FIG. **1**C, for example, the drift tube funnel $\mathbf{32}_2$ is coupled at its ion outlet to an ion inlet of a drift tube sub-section $\mathbf{30}_5$, and an ion outlet of the drift tube sub-section $\mathbf{30}_5$ is coupled to an ion inlet of the drift tube funnel $\mathbf{32}_3$ (corresponding to the drift tube funnel $\mathbf{32}_9$ in FIG. **1**A). In this embodiment, the single-pass drift tube **12"** is thus a linear drift tube made up of the linear drift tube segments D**1** and D**2** joined by a linear drift tube segment DT made up of the drift tube sub-section $\mathbf{30}_5$. The multiple-pass drift tube **14'** is, in the embodiment illustrated in FIG. **1**C, a closed-path drift tube made up of four curved drift tube sub-sections $\mathbf{34}_1$-$\mathbf{34}_4$ each coupled between a different two of four drift tube funnels $\mathbf{32}_5$-$\mathbf{32}_8$. A drift tube section $\mathbf{30}_8$ has an ion inlet coupled to the drift tube sub-section $\mathbf{30}_5$ of the single-pass drift tube **12"** and an ion outlet coupled to an ion inlet of a drift tube section **35**. An ion outlet of the drift tube section **35** is coupled to the drift tube sub-section $\mathbf{34}_2$ of the multiple pass drift tube **14'**. In some embodiments, such as that illustrated in FIG. **1**C, the drift tube section **35** may include an inlet/outlet, i.e. bi-directional, funnel which may be controlled in a conventional manner, e.g., via one or more voltage sources, to direct and focus ions moving from the single-pass drift tube **12"** into the multiple-pass drift tube **14'** via the drift tube sub-section $\mathbf{30}_8$, and which may also be controlled in a conventional manner, e.g., via one or more voltage sources, to direct and focus ions moving from the multiple-drift tube **14'** into the single-pass drift tube **12"** via the drift tube sub-section $\mathbf{30}_8$. In other embodiments, the bi-directional funnel may be replaced with another funnel structure or other mechanism (e.g., structure and/or energy source(s)), or omitted altogether. In any case, the drift tube sections $\mathbf{30}_8$, **35** form a T-connection between the single pass drift tube **12"** and the multiple-pass drift tube **14'**.

The embodiment illustrated in FIG. **1**C includes three ion gates G**1**-G**3** which are controllable, as will be described in detail below, to confine ions within the single-pass drift tube **12"**, to confine ions within the multiple-pass drift tube **14'**, to pass or divert at least some of the ions in the single-pass drift tube **12"** into the multiple-pass drift tube **14'** and/or to pass or divert at least some of the ions in the multiple-pass drift tube **14'** back into the single-pass drift tube **12"**. A first one of the ion gates, G**1**, is illustratively positioned in the drift tube sub-section $\mathbf{30}_5$ at or just beyond the ion inlet of the drift tube section $\mathbf{30}_8$. A second one of the ion gates, G**2**, is illustratively positioned in the drift tube section $\mathbf{30}_8$ at or just beyond the ion inlet thereof. A third one of the ion gates, G**3**, is illustratively positioned in the drift tube section **35** at or near the ion outlet thereof. It will be understood that the hybrid ion mobility spectrometer **10"** may include more or fewer such ion gates, and that any such alternative embodiment of the hybrid ion mobility spectrometer is contemplated by this disclosure.

Referring now to FIGS. **1**D-**1**F, yet another alternate embodiment of a hybrid ion mobility spectrometer **10'"** is shown. The hybrid ion mobility spectrometer **10'''** is also identical in many respects to the hybrid ion mobility spectrometers **10** and **10"** illustrated in FIGS. **1**A and **1**C respectively and described above. Like features are identified by like reference numbers, and a detailed description of common features between the spectrometers **10**, **10"** and **10'''** will not be repeated here for brevity. It will be further understood that the various embodiments of the various components and aspects to the hybrid ion mobility spectrometer **10** and **10"** described above apply equally to the hybrid ion mobility spectrometer **10'''**.

In one aspect, the hybrid ion mobility spectrometer **10'''** illustrated in FIGS. **1**D-**1**F differs from the hybrid ion mobility spectrometer **10** and **10"** illustrated in FIGS. **1**A and **1**C respectively in that an ion travel axis **70** of the multiple-pass drift tube **14"**, i.e., an axis defined, or parallel with an axis defined, centrally through the multiple-pass drift tube **14"** and along which ions travel through the multiple-pass drift tube **14"**, lies in a plane that is different from the plane in which an ion travel axis **72** of the single-pass drift tube **12'''**, i.e., an axis defined, or parallel with an axis defined, centrally through the single-pass drift tube **12'''** and along which ions travel through the single-pass drift tube **12'''**, lies. In the illustrated embodiment, the planes in which the ion travel axes **70** and **72** lie are orthogonal, although it will be understood that this disclosure contemplates embodiments in which the two different planes in which the ion travel axes **70** and **72** lie are not orthogonal.

In another aspect, the hybrid ion mobility spectrometer **10'''** illustrated in FIGS. **1**D-**1**F differs from the hybrid ion mobility spectrometer **10** and **10"** illustrated in FIGS. **1**A and **1**C respectively in that, in contrast to a drift tube transition section, DT, the hybrid ion mobility spectrometer **10'''** defines a transition region **80** (TR) as an interface between the single-pass drift tube **12'''** and the multiple-pass drift tube **14"**. Referring specifically to FIG. **1**F, an example embodiment of the transition region **80** is illustrated. In this embodiment, the transition region **80** includes a first plate **82** defining an ion passage, e.g., opening, **90** therethrough, which represents an ion inlet to the transition region **80** positioned adjacent to the ion outlet of the drift tube funnel $\mathbf{32_2}$ (e.g., see FIG. **1**E). Another plate **84** is positioned opposite to the plate **80** and defines another ion passage, e.g., opening, **92** therethrough (both shown by dashed-line representation in FIG. **1**F), which represents an ion outlet of the transition region **80** positioned adjacent to the ion inlet of the drift tube funnel $\mathbf{32_3}$. A third plate **86** is positioned between the plates **82** and **84** along one side thereof, and a fourth plate **88** is positioned between the plates **82** and **84** along another side thereof. The third and fourth plates **86**, **88** each define an ion passage, e.g., opening, therethrough which represent an ion inlet/outlet to/of the transition region **80** with the opening defined through the plate **86** positioned adjacent to the ion inlet/outlet of the drift tube sub-section $\mathbf{34_1}$ and the opening defined through the plate **88** positioned adjacent to the ion inlet/outlet of the drift tube section $\mathbf{34_2}$. One or more of the plates **82**, **84**, **86**, **88** may illustratively be operated as an ion gate, such that the illustrated embodiment may include one or more of G**1**-G**4**.

As described briefly hereinabove, the ion gates G**1**-G**3** of the hybrid ion mobility spectrometers **10** and **10"** and the ion gates G**1**-G**4** of the hybrid ion mobility spectrometer **10'** and **10'''** are controllable to confine ions within the single-pass drift tube **12**, **12'**, **12"**, **12'''**, to confine ions within the multiple-pass drift tube **14**, **14'**, **14"** to pass or divert at least some of the ions in the single-pass drift tube **12**, **12'**, **12"**, **12'''** into the multiple-pass drift tube **14**, **14'**, **14"** and/or to pass or divert at least some of the ions in the multiple-pass drift tube **14**, **14'**, **14"** back into the single-pass drift tube **12**, **12'**, **12"**, **12'''**. Referring now to FIGS. **3**A and **3**B, a flowchart is shown illustrating a process **100** for controlling the hybrid ion mobility spectrometer **10**, **10'**, **10"**, **10'''** according to a number of different operational modes of the hybrid ion mobility spectrometer **10**, **10'**, **10"**, **10'''** in which the set of ion gates, e.g., ion gates G**1**-G**3** for the spectrometers **10**, **10"** and ion gates G**1**-G**4** for the spectrometer **10'**, **10'''**, are controlled as described above. In one embodiment, some or all of the process **100** may be controlled by the processor **42** in accordance with instructions stored in a memory of the processor **42**. Alternatively or additionally, some or all of the process **100** may be controlled by programming one or more of the one or more voltage sources **40** in embodiments in which one or more of the voltage sources **40** are programmable. Some of the process **100** may be alternatively or additionally carried out manually.

In any case, the process **100** begins at step **102** where the ion source **18** is controlled in a conventional manner to generate ions, e.g., in embodiments in which the ion source **18** is or includes an ion generation structure for generating ions from a sample, or to otherwise supply ions, e.g., in embodiments in which the ion source **18** is another ion separation instrument and/or other ion processing instrument that does not itself generate ions but rather operates on ions generated elsewhere. Thereafter at step **104**, at least some of the generated or otherwise supplied ions are introduced into the ion inlet **16** of the single-pass drift tube **12**, **12'**, **12"**, **12'''**, e.g., by controlling a conventional ion gate positioned at the ion inlet **16** to pass ions therethrough and into the single-pass drift tube **12**, **12'**, **12"**, **12'''**, by drawing generated ions into the single-pass drift tube **12**, **12'**, **12"**, **12'''** using a static or dynamic electric field, or the like. At step **106**, an electric drift field is established within the single-pass drift tube **12**, **12'**, **12"**, **12'''**, which may occur before or after step **104**.

In any case, the process **100** advances to step **108** where the ion gates, e.g., G**1**-G**3** in the case of the hybrid ion mobility spectrometer **10**, **10"** and G**1**-G**4** in the case of the hybrid ion mobility spectrometer **10'**, **10'''**, are controlled to direct ions in the single-pass drift tube **12**, **12'**, **12"**, **12'''** therethrough and through the ion outlet **20**, i.e., to confine ions within the single-pass drift tube **12**, **12'**, **12"**, **12'''** such that the ions drift only through the single-pass drift tube **12**, **12'**, **12"**, **12'''** from the ion inlet **16** to the ion outlet **20** thereof and not through the multiple-pass drift tube **14**, **14'**, **14"**. In the single-pass drift tube **12** illustrated in FIG. **1**A, step **108** may be carried out by controlling G**1** to the closed or ion-blocking position and controlling G**2** and G**3** to the open or ion-passing position, such that ions entering the ion inlet **16** pass sequentially through D**1**, DT and D**2** of the single-pass drift tube **12**. In the single-pass drift tube **12'** illustrated in FIG. **1**B, step **108** may be carried out by controlling G**1** to the closed or ion-blocking position and controlling G**2** to the open or ion-passing position, such that ions entering the ion inlet **16** pass sequentially through D**1**, D**3** and D**2** of the single-pass drift tube **12'**. In the single-pass drift tube **12"** illustrated in FIG. **1**C, step **108** may be carried out by controlling G**1** to the open or ion-passing position and controlling G**2** to the closed or ion-blocking position, such that ions entering the ion inlet **16** pass sequentially through D**1**, DT and D**2** of the single-pass drift tube **12"**. In the single-pass drift tube **12'''** illustrated in FIGS. **1**D-**1**F, step **108** may be carried out by controlling G**1**, e.g., the opening **90** through the plate **82**, to the open or ion-passing position and controlling G2, e.g., the opening **92** through the plate **84**, to the open or ion-passing position, and likewise controlling the gates G3, G4, e.g., the openings through the plates **86**, **88** respectively to the closed or ion blocking positions, such that ions entering the ion inlet **16** pass sequentially through D1, TR and D2 of the single-pass drift tube **12'''**. In each case, ions generated at or otherwise supplied by the ion source **18** travel, i.e., drift, through only the single-pass drift tube **12**, **12'**, **12''**, **12'''** under the influence of the electric field established therein where they separate in time as a first function of ion mobility defined by the various structural dimensions and operating parameters of the single-pass drift tube **12**, **12'**, **12''**, **12'''**.

Following step **108**, the process **100** advances to step **110** where an ion mobility range of interest is determined based on at least some of the ions exiting the single-pass drift tube **12**, **12'**, **12''**, **12'''**. As described above, it may be discovered upon analysis of ion spectral information resulting from the detection of ions exiting the ion outlet **20** of the single-pass drift tube **12**, **12'**, **12'**, **12''''** pursuant to step **108** that a subset, e.g., two or more, of ion intensity peaks in a particular range of ion mobilities (or ion drift times) are crowded together and cannot be satisfactorily resolved over the length of the single-pass drift tube **12**, **12'**, **12''**, **12'''**. Such a range of ion mobilities may then be the ion mobility range of interest. In other cases, the ion mobility range of interest may be determined based on one or more alternate or additional criteria. In some cases, the ion mobility range of interest may be the same as that produced by the single-pass drift tube **12**, **12'**, **12''**, **12'''**, and in other cases the ion mobility range of interest may be different as just described. Likewise, whereas the single-pass drift tube **12**, **12'**, **12''**, **12'''** is generally operable to separate ions according to a first function of ion mobility and the multiple-pass drift tube **14**, **14'**, **14''** is generally operable to separate ions according to a second function of ion mobility, the first and second functions of ion mobility may be the same in some embodiments and different in others.

In one embodiment, the process **100** includes a step **112** as shown in dashed-line representation, and in this embodiment the process **100** advances from step **110** to step **114** wherein the single-pass drift tube **12**, **12'**, **12''**, **12'''** is cleared of ions, e.g., by stopping the generation of ions by the ion source **18** and allowing the tube **12**, **12'**, **12''**, **12'''** to clear. Thereafter at step **116**, the ion source **18** is controlled to begin generating ions again, and thereafter at step **118** at least some of the generated ions are introduced into the single-pass drift tube **12**, **12'**, **12''**, **12'''** as described above with respect to step **104**. In alternate embodiments, the process **100** does not include step **112** and in some such embodiments the ion source **18** may be controlled to continually, periodically or intermittently generate ions while in other embodiments the ion source **18** may be started and then stopped, but ions need not be cleared from the single-pass drift tube **12**, **12'**, **12''**, **12'''** before continuing to step **120**.

At step **120**, the set of ion gates, e.g., G1-G3 in the case of the hybrid ion mobility spectrometer **10**, **10''** and G1-G4 in the case of the hybrid ion mobility spectrometer **10'**, **10'''**, is controlled to divert or pass some or all of the ions in or entering the single-pass drift tube **12**, **12'**, **12''**, **12'''** into the multiple-pass drift tube **14**, **14'**, **14''**, and at step **122** an electric field is established within the multiple-pass drift tube **14**, **14'**, **14''** to cause ions to drift through the multiple-pass drift tube **14**, **14'**, **14''**. In the single-pass drift tube **12** illustrated in FIG. 1A, step **120** may be carried out by controlling G1 and G3 to their open or ion-passing positions and controlling G2 to the closed or ion-blocking position, such that ions entering the ion inlet **16** pass sequentially through D1, through part of DT and into the multiple-pass drift tube **14**. In the single-pass drift tube **12'** illustrated in FIG. 1B, step **120** may be carried out by controlling G1 and G3 to their open or ion-passing positions, and controlling G2 and G4 to their closed or ion-blocking positions, such that ions entering the ion inlet **16** pass from D1 directly into the multiple-pass drift tube **14**. In the single-pass drift tube **12''** illustrated in FIG. 1C, step **120** may be carried out by controlling G1 to the closed or ion-blocking position, and controlling G2 and G3 to their open or ion-passing positions with the electric drift field in the drift tube sections $\mathbf{30}_8$ and **35** controlled to pass ions moving through D1 into the multiple-pass drift tube **14'**. In the single-pass drift tube **12'''** illustrated in FIGS. 1D-1F, step **120** may be carried out by controlling G1, e.g., the opening **90** through the plate **82**, to the open or ion-passing position, controlling G2, e.g., the opening **92** through the plate **84**, to the closed or ion-blocking position, and controlling the gates G3 and/or G4, e.g., the openings through the plates **86**, **88** respectively to the open or ion-passing positions, such that ions entering the ion inlet **16** pass from D1 through TR and directly into the multiple-pass drift tube **14''**. Ions generated at the ion source **18** thus travel, i.e., drift, through the single-pass drift tube **12**, **12'**, **12''**, **12'''** under the influence of the electric field established therein where they separate in time as a first function of ion mobility defined by the various structural dimensions and operating parameters of the single-pass drift tube **12**, **12'**, **12''**, **12'''**, and after passage of some or all of such ions into the multiple-pass drift tube **14**, **14'**, **14''** the ions travel, i.e., drift, through the multiple-pass drift tube **14**, **14'**, **14''** under the influence of the electric field established therein where they separate in time as a second function of ion mobility defined by the various structural dimensions and operating parameters of the multiple-pass drift tube **14**, **14'**, **14''**. The first and second functions of ion mobility may be the same in some embodiments and different in others.

At step **124**, the set of ion gates, e.g., G1-G3 in the case of the hybrid ion mobility spectrometer **10**, **10''** and G1-G4 in the case of the hybrid ion mobility spectrometer **10'**, **10'''**, is controlled to cause ions within the multiple-pass drift tube **14**, **14**, **14''** to travel one or multiple times through or about the multiple-pass drift tube **14**, **14'**, **14''**. The number of times the ions travel through or about the multiple-pass drift tube **14**, **14'**, **14''** will typically be dictated by the total length of the multiple-pass drift tube **14**, **14'**, **14''** needed to adequately resolve the ion peaks of interest, or by other additional or alternate criteria. In the single-pass drift tube **12** illustrated in FIG. 1A, step **124** may be carried out by maintaining G1 in its open or ion-passing position and G2 in its closed or ion-blocking position, and controlling G3 to its closed position such that the multiple-pass drift tube **14** is completely closed to the single-pass drift tube **12**. In the single-pass drift tube **12'** illustrated in FIG. 1B, step **124** may be carried out by maintaining G3 and in its open or ion-passing position and G4 in its closed or ion-blocking position, and controlling G1 to its closed or ion-blocking position such that the multiple-pass drift tube **14** is completely closed to the single-pass drift tube **12'**. In the single-pass drift tube **12''** illustrated in FIG. 1C, step **124** may be carried out by controlling G2 and/or G3 to closed or ion-blocking position, such that the multiple-pass drift tube **14'** is completely closed to the single-pass drift tube **12''**. In the single-pass drift tube **12'''** illustrated in FIGS. 1D-1F, step **124** may be carried out by controlling G1, G2, e.g., the openings through the plates **82**, **84** respectively, to their closed or ion-blocking positions, and controlling G3, G4, e.g., the openings through the plates **86**, **88** respectively, to their open or ion-passing positions, such that the multiple-pass drift tube **14"** is completely closed to the single-pass drift tube **12'"**. The ions then travel, i.e., drift, through the multiple-pass drift tube **14**, **14'**, **14"** under the influence of the electric field established therein where they separate in time as a second function of ion mobility defined by the various structural dimensions and operating parameters of the multiple-pass drift tube **14**, **14'**, **14"**.

In one embodiment, step **126** is included, and at step **126** the electric drift field established within the multiple-pass drift tube **14**, **14'**, **14"** is controlled to cause only ions within the ion mobility range of interest to travel through the multiple-pass drift tube **14**, **14'**, **14"**. For example, the open/closed timing of the various ion gates (G1-G3 or G1-G4) may be controlled at step **120** to pass ions of all mobilities from the single-pass drift tube **12**, **12'**, **12"**, **12'"** into the multiple-pass drift tube **14**, **14'**, **14"**, and in such embodiments, electric fields within the sub-sections **34** and funnels **32** of the multiple-pass drift tube **14**, **14'**, **14"** are sequentially switched on and off in a conventional manner at a rate that allows only ions within the ion mobility range of interest to traverse the multiple-pass drift tube **14**, **14'**, **14"**. In some alternate embodiments, the open/closed timing of the ion gates G1-G3 (or G1-G4) may be controlled at step **120** such that only ions within the ion mobility range of interest are passed from the single-pass drift tube **12**, **12'**, **12"**, **12'"** into the multiple-pass drift tube **14**, **14'**, **14"**, and in such embodiments step **126** may be carried out simply by controlling the application of the electric fields within the sub-sections **34** and funnels **32** of the multiple-pass drift tube **14**, **14'**, **14"** to pass ions of all ion mobilities or by sequentially switching such electric fields on and off at a rate that allows only ions within the ion mobility range of interest to continue to traverse the multiple-pass drift tube **14**, **14'**, **14"**.

After the ions have traveled the multiple times through the multiple-pass drift tube **14**, **14'**, **14"** the set of ion gates, e.g., G1-G3 in the case of the hybrid ion mobility spectrometer **10**, **10"** and G1-G4 in the case of the hybrid ion mobility spectrometer **10'**, **10'"** is controlled at step **128** to pass at least some of the ions from the multiple-pass drift tube **14**, **14'**, **14"** back into the single-pass drift tube **12**, **12'**, **12"**, **12'"**. In the single-pass drift tube **12** illustrated in FIG. **1**A, step **128** may be carried out by controlling G1 to the closed or ion-blocking position and controlling G2 to the open or ion-passing position, such that ions traveling through the multiple-pass drift tube **14** pass back into the single-pass drift tube **12**, i.e., sequentially via the Y-shaped drift tube segment $\mathbf{36}_2$, the drift tube funnel $\mathbf{32}_4$ and the curved drift tube sub-section $\mathbf{34}_2$. In the single-pass drift tube **12'** illustrated in FIG. **1**B, step **128** may be carried out by controlling G3 to the closed or ion-blocking position and controlling G4 to the open or ion-passing position, such that ions traveling through the multiple-pass drift tube **14** pass back into the single-pass drift tube **12'**, i.e., sequentially via the Y-shaped drift tube segment $\mathbf{36}_2$, the drift tube funnel $\mathbf{32}_4$ and the curved branch of the Y-shaped drift tube sub-section $\mathbf{38}_2$. In the single-pass drift tube **12"** illustrated in FIG. **1**C, step **128** may be carried out by controlling G1, G2 and G3 to their open or ion-passing positions with the electric fields in the drift tube sections $\mathbf{30}_8$ and **35** set to direct ions from the drift tube $\mathbf{34}_2$ to the drift tube sub-section $\mathbf{30}_5$. In the single-pass drift tube **12'"** illustrated in FIGS. **1**D-**1**F, step **128** may be carried out by controlling G1 and either G3 or G4, e.g., the openings through the plates **82** and **86** or **88** respectively, to their closed or ion-blocking positions, and controlling G2 and the other of G3 or G4, e.g., the openings through the plates **84** and **88** or **86** respectively, to their open or ion-passing positions, such that ions traveling through the multiple-pass drift tube **14"** pass back into the single-pass drift tube **12'"** via the transition region **80**.

In one embodiment, ions re-entering the single-pass drift tube **12**, **12'**, **12"**, **12'"** travel, i.e., drift, through the remainder of the single-pass drift tube **12**, **12'**, **12"** toward and through the ion outlet **20** under the influence of the electric field established therein where they separate in time in D2 according to the first function of ion mobility. In some alternate embodiments, the open/closed timing of the ion gates G1-G3 (or G1-G4) may be controlled at step **120** such that ions within all ion mobility ranges are passed from the single-pass drift tube **12**, **12'**, **12"**, **12'"** into the multiple-pass drift tube **14**, **14'**, **14"**, step **126** may be replaced by a step in which the open/closed timing of the ions gates G1-G3 (or G1-G4) are likewise controlled such that ions within all ion mobility ranges travel through the multiple-pass drift tube **14**, **14'**, **14"**, step **128** may be modified to control the open/closed timing of the ion gates G1-G3 (or G1-G4) such that ions within all ion mobility ranges are passed from the multiple-pass drift tube **14**, **14'**, **14"** back into the single-pass drift tube **12**, **12'**, **12"**, **12'"**, and one or more additional ion gates within D2, e.g., an ion gate positioned at the ion outlet **20**, may be controlled by selectively controlling the open/closed positions of the one or more additional ion gates, e.g., relative to an opening/closing of one or more upstream ion gates, such that only ions within the ion mobility range of interest exit the ion outlet **20** of the single-pass drift tube **12**, **12'**, **12"**, **12'"**.

Ions traveling through the ion outlet **20** are detected at step **130** by the ion detector, and thereafter at step **132** the detected ions are processed by the processor **42** to produce corresponding ion spectral information, e.g., as a function of ion drift time.

In an alternate embodiment, the process **100** illustratively includes a step **134** between steps **120** and **122** such that the single-pass drift tube **12**, **12'**, **12"**, **12'"** and the multiple-pass drift tube **14**, **14'**, **14"** operate in parallel as described hereinabove. In one embodiment, step **134** may include steps **102**-**110** as illustrated in FIG. **3**A. In other embodiments, step **134** may include only steps **102**-**108**, and in still other embodiments in which ions are generated or otherwise supplied continually, intermittently or periodically step **134** may include only steps **104**-**108** or **104**-**110**. In other embodiments still, step **134** may include more, fewer and/or other steps than those just described. In any such embodiments, one or more of the ion gates in the set of ion gates, e.g., G1-G3, may be controlled to one or more intermediate positions between the open and closed positions to direct some of the ions traveling through the single-pass drift **12** into the multiple-pass drift tube **14** while also allowing others of the ions traveling through the single-pass drift tube **12** to travel completely through the single-pass drift tube **12**, e.g., to and through the outlet **20** thereof. In such a parallel operating mode, ions supplied by the single or common ion source **18** to the inlet **16** of the single-pass drift tube **12** thus travel in parallel through the single-pass drift tube **12** and also through the combination of the single-pass drift tube **12** and the multiple-pass drift tube **14**, with some of the ions traveling directly through the single-pass drift tube **12** to and through the ion outlet **20** and others of the ions traveling through the single-pass drift tube **12**, to and through the multiple-pass drift tube **14**, then back to and through any remaining section(s) of the single-pass drift tube **12** and exiting the ion outlet **20** of the single-pass drift tube **12**.

In the embodiments illustrated in FIGS. **1**A-**1**F, the variously located ion gates, e.g., G**1**-G**3**, are disclosed as being controllable in a conventional manner to selectively allow ions to pass therethrough or to selectively block ions from passing therethrough, and/or as being controllable in a conventional manner to selectively allow passage therethrough of only a portion of the ions traveling toward such gates. In some embodiments, one or more, or all, such ion grates are disclosed as being provided in the form of a mesh or grid suitably controlled by one or more conventional DC voltage sources. In some alternate embodiments, one or more, or all, such ion gates are disclosed as being provided in the form of a non-meshed, e.g., grid-less, structure defining an ion passageway therethrough and suitably controlled by one or more conventional DC voltage sources and/or RF voltage sources to selectively block or allow passage of ions therethrough. In still other alternate embodiments, e.g., as illustrated in FIGS. **1**D-**1**F for example, any such ion gates are disclosed as being implemented in, or as part of, one or more ion inlet and/or outlet plates of an ion transition region **80** in which the one or more ion gates are controlled in a conventional manner to selectively control the direction of ion travel within the hybrid ion mobility spectrometer **10'''**.

In each of the embodiments **10**, **10'**, **10''**, **10'''** of the hybrid ion mobility spectrometers illustrated in FIGS. **1**A-**1**F and described above, ion gates are positioned at specific locations therein and are controlled as described to selectively cause ions drifting in an axial direction along and through a drift tube or drift tube segment to either continue to travel in and along the same axial direction, or to divert or redirect the ions to travel in a different direction along and axially through a different drift tube or drift tube section. In some cases, such as with the ion gate pair G**1** and G**2** in the embodiment **10** illustrated in FIG. **1**A and the gate pairs G**1**, G**2** and G**3**, G**4** in the embodiment **10'** illustrated in FIG. **1**B, the different directions of travel differ by an acute angle, and in other cases, such as with the ion gate pair G**1** and G**2** in the embodiment **10''** illustrated in FIG. **1**C and the ion gates associated with one or more of the plates **82**, **84**, **86**, **88** in the embodiment **10'''** illustrated in FIGS. **1**D-**1**F, the different directions of travel are transverse to each other, e.g., normal or approximately normal relative to each other.

In any of the hybrid ion mobility spectrometer embodiments **10**, **10'**, **10''**, **10'''** illustrated in FIGS. **1**A-**1**F and described above, one or more such ion gates and/or pairs of ion gates may illustratively be replaced by a single, gateless ion steering channel. Advantageously, and as will become apparent from the following description, such an ion steering channel does not operate, as the ion gate embodiments described above, to selectively block and allow passage of ions; rather, such an ion steering channel is controllable, e.g., via application of suitable DC voltages, to selectively steer or guide ions along different directions of ion travel to thereby direct or redirect ions into and through various drift tubes and/or drift tube sections of the spectrometer **10**, **10'**, **10''**, **10'''**. Ion loss is thus decreased by using one or more such ion steering channels since ions will not be blocked, and thus not lost as with conventional ion gates, and ion concentration in the hybrid ion mobility spectrometers **10**, **10'**, **10''**, **10'''** will accordingly be increased.

An example embodiment of an ion steering or guiding structure **200** is illustrated in FIG. **4**A, and is provided in the form of an transition region, similar or identical to the transition region **80** illustrated in FIG. **1**F, in which an embodiment of an ion steering channel **210** is disposed in place of the ion gates G**1**-G**4**. For purposes of this disclosure, the transition region **200** and ion steering channel **210** will be described as replacing the transition region **80** illustrated in FIG. **1**E, although it will be understood that the transition region **200** and/or the ion steering channel **210** alone may be implemented as is, or in other forms, in one or more locations in any of the hybrid ion mobility spectrometers **10**, **10'**, **10''**, **10'''** illustrated in FIGS. **1**A-**1**F and described above. In the embodiment illustrated in FIG. **4**A, the transition region **200** illustratively includes a first plate **202** defining an ion passage, e.g., opening, **202**A therethrough, which represents an ion inlet to the transition region **200** positioned adjacent to, e.g., the ion outlet of the drift tube funnel $\mathbf{32}_2$ (e.g., see FIG. **1**E). Another plate **208** opposite to and facing the plate **202** is spaced apart from the plate **202** and illustratively defines an ion passage **208**A, e.g., opening, therethrough identical or similar to the opening **202**A, which represents an ion outlet of the transition region **200** positioned adjacent to the ion inlet of the drift tube funnel $\mathbf{32}_3$. A third plate **204** is positioned between the plate **202** and the plate **208** along one side of the transition region **200**, and a fourth plate **206** is positioned opposite the plate **204**. The third and fourth plates **204**, **206** each define an ion passage, e.g., opening, therethrough which represents an ion inlet/outlet to/of the transition region **200** with the opening defined through the plate **204** positioned adjacent to the ion inlet/outlet of the drift tube sub-section $\mathbf{34}_1$ and the opening defined through the plate **206** positioned adjacent to the ion inlet/outlet of the drift tube section $\mathbf{34}_2$.

Positioned within the transition region **200** illustrated in FIG. **4**A is an embodiment of an ion steering channel **210** including planar structures **212**, **214** spaced apart from each other by an ion directing channel **216** such that planes defined by each of the planar structures **212**, **214** are parallel with each other so that the channel **216** is defined therebetween and such that the planes defined by each of the planar structures **212**, **214** are generally normal or approximately normal to planes defined by each of the plates **202**, **204**, **206**, **208**. As illustrated in FIG. **4**A, the ion steering channel **210** is positioned within the transition region **200** such that the channel **216** defined between the planar structures **212**, **214** is illustratively aligned centrally or axially with the ion passages, e.g., **202**A, **208**A, defined through the plates of the transition region **200** so that ions passing through the openings or ion passages defined through the plates of the transition region **200**, e.g., openings or ion passages **202**A, **208**A, either enter into or exit from the channel **216** in generally in a direction parallel to the planes defined by the opposed inner surfaces of the planar structures **212**, **214**. An alternate embodiment of an ion steering or guiding structure **200'** is illustrated in FIG. **4**B, and in the embodiment depicted in FIG. **4**B the ion steering or guiding structure **200'** illustratively includes the ion steering channel **210** as just described which is illustratively bounded on each side by opposing sidewalls **204'**, **206'** each defining an ion passageway therethrough which is approximately sized identically or complementarily to the channel **216**. In some alternate embodiments, the opposing sidewalls **204'**, **206'** may be replaced or supplemented with a similarly or identically configured front wall and/or a similarly or identically configured rear wall.

In some embodiments, the planar structures **212**, **214** of the ion channel **210** are each illustratively provided in the form of a conventional circuit board having a plurality of electrically conductive surfaces or pads formed in a conventional manner on an inner, major surface thereof and each electrically connectable to a suitable voltage source, e.g., a DC or other voltage source. The electrically conductive surfaces or pads formed on the circuit board **212** are illustratively identical and complementary to those formed on the circuit board **214** such that the electrically conductive surfaces or pads formed on the circuit board **212** are juxtaposed with corresponding ones of the electrically conductive surfaces or pads formed on the circuit board **214** when the inner surfaces of the circuit boards **212**, **214** are spaced apart to define the channel **216** as illustrated in FIGS. **4**A and **4**B. The circuit boards **212**, **214** may illustratively be conventional printed circuit boards ("PCB's") or other conventional circuit boards formed of one or more conventional electrically insulating or non-conductive materials, e.g., fiber-reinforced or paper-reinforced epoxy resin, alumina, one or more ceramic materials, etc., and the electrically conductive surfaces or pads may be formed of one or more conventional electrically conductive materials, e.g., copper, aluminum and/or other metallic or non-metallic but electrically conductive materials. The circuit boards **212**, **214** may illustratively use through-hole, surface-mounting and/or other structures and techniques for mounting electrical components and/or connecting electrical power sources thereto.

Referring now to FIG. **5**, an example embodiment is shown of the inner, major surface **212**A one of the planar circuit boards **212** of FIGS. **4**A and **4**B upon which a pattern of 4 substantially identical and spaced apart electrically conductive pads **220**A-**220**D are formed. The inner, major surface **214**A of the planar circuit board **214** has an identical pattern of 4 electrically conductive pads **220**A'-**220**D' formed thereon, and the electrically conductive pads **220**A-**220**D are juxtaposed over corresponding ones of the electrically conductive pads **220**A'-**220**D' when the inner, major surface **212**A of the circuit board **212** is spaced apart from and generally parallel with the inner, major surface **214**A of the circuit board **214** so that the inner, major surfaces **212**A and **214**A define the channel **216** therebetween as illustrated in FIG. **6**. In one embodiment, the distance, D_P, of the channel or space **216** defined between the inner surfaces **212**A, **214**A of the circuit boards **212**, **214** is approximately 5 cm, although in other embodiments the distance D_P may be greater or lesser than 5 cm, and it will be understood that the distance D_P will depend, at least in part, on the particular application in which the ion steering channel **210** is implemented.

Referring now to FIG. **6**, the planar circuit board **212** is shown illustratively spaced apart from the planar circuit board **214** such that upstream edges **212**C and **214**C of the respective circuit boards **212**, **214** are aligned, as are downstream edges **212**D, **214**D and opposing side edges **212**E, **214**E and **212**F, **214**F. The terms "upstream" and "downstream" illustratively refer to the direction of ion travel such that, in the embodiment illustrated in FIG. **4**A, for example, the aligned edges **212**C, **214**C are positioned in contact with or adjacent to the plate **202** such that the channel **216** is axially aligned with the opening **202**A, and the aligned edges **212**D, **214**D are positioned in contact with or adjacent to the plate **208** such that the channel **216** is axially aligned with the opening **208**A. In any case, the major surface **212**B of the planar circuit board **212** opposite the inner, major surface **212**A will illustratively be referred to as the outer surface of the planar circuit board **212**, and the major surface **214**B of the planar circuit board **214** opposite the inner, major surface **214**A will illustratively be referred to as the outer surface of the planar circuit board **214**.

In the embodiment illustrated in FIG. **6**, a first DC voltage source DC**1** is electrically connected to each of the juxtaposed electrically conductive pads **220**A, **220**A' such that the potential at both pads **220**A, **220**A' is the potential produced by DC**1**, a second DC voltage source DC**2** is electrically connected to each of the juxtaposed electrically conductive pads **220**C, **220**C' such that the potential at both pads **220**C, **220**C' is the potential produced by DC**2**, a third DC voltage source DC**3** is electrically connected to each of the juxtaposed electrically conductive pads **220**B, **220**B' such that the potential at both pads **220**B, **220**B' is the potential produced by DC**3**, and a fourth DC voltage source DC**4** is electrically connected to each of the juxtaposed electrically conductive pads **220**D, **220**D' such that the potential at both pads **220**D, **220**D' is the potential produced by DC**4**. In some embodiments, one or more conventional electrical components, e.g., resistors or other components, may be interconnected between one or more of the voltage sources DC**1**-DC**4** and one or more of the corresponding electrically conductive pads **220**A-**220**D and **220**A'-**220**D' and/or between two or more, and/or two or opposed pairs, of the electrically conductive pads **220**A-**220**D and **220**A'-**220**D'. In the illustrated embodiment, each of the DC voltage sources DC**1**-DC**4** is independently controlled, e.g., via manually or via the processor **42**, although in alternate embodiments two or more of the DC voltage sources DC**1**-DC**4** may be controlled together as a group. In any case, it will be understood that although the voltage sources DC**1**-DC**4** are illustrated and disclosed as being DC voltage sources, this disclosure contemplates other embodiments in which one or more of the voltage sources DC**1**-DC**4** is or includes an AC voltage source such as, for example, an RF voltage source suitably coupled, e.g., capacitively, via conventional electrical components to corresponding ones or pairs of the electrically conductive pads **220**A-**220**D and **220**A'-**220**D'.

Referring now to FIGS. **7**A and **7**B, operation of the ion steering channel **210** illustrated in FIG. **6** will be described as implemented in the form of the ion steering or guiding structure **200** or **200**' in place of the ion transition region **80** of the ion mobility spectrometer **10**''' illustrated in FIGS. **1**D-**1**F. It will be understood, however, that the ion steering channel **210** may alternatively or additionally be implemented in place of one or more ion gates in one or more of the other embodiments **10**, **10**', **10**'' of the ion mobility spectrometer described above. In any case, the DC voltage sources DC**1**-DC**4** are omitted in FIGS. **7**A and **7**B for clarity of illustration, and instead the various DC voltages produced thereby and applied to the connected pairs of electrically conductive pads **220**A/**220**A', **220**B/**220**B', **220**C/**220**C' and **220**D/**220**D' are represented graphically. Referring specifically to FIG. **7**A, the ion steering channel **210** is shown in a state in which a reference potential, V_{REF}, is applied by each of DC**1** and DC**2** to the electrically conductive pad pairs **220**A/**220**A' and **220**C/**220**C' respectively, and a potential −XV, less than V_{REF}, is applied by each of DC**3** and DC**4** to the electrically conductive pad pairs **220**B/**220**B' and **220**D/**220**D' respectively. Illustratively, V_{REF} may be any positive or negative voltage, or may be zero volts, e.g., ground potential, and −XV may be any voltage, positive, negative or zero voltage that is less than V_{REF} so as to establish an electric field E**1** which is parallel with the sides **212**E, **214**E and **212**F, **214**F of the circuit boards **212**, **214** and which extends in a direction from and generally normal to the upstream edges **212**C, **214**C toward and normal to the downstream edges **212**D, **214**D of the circuit boards **212**, **214** as depicted in FIG. **7**A. With the electric field, E**1**, established as illustrated in FIG. **7**A, ions **230** drifting through the drift tube segment 32_2 of the single-pass drift tube 12''' enter the channel 216 between the upstream edges 212C, 214C and are steered or guided (or directed) by the electric field, E1, in a direction generally parallel with the ion travel axis 72 of the drift tube 12''', and such ions thus pass into the drift tube segment 323 of the single-pass drift tube 12''' as described above with respect to FIGS. 1D-1F.

Referring now to FIG. 7B, when it is desired to direct ions from the single-pass drift tube 12''' into the multiple-pass drift tube 14'', as also described above with respect to FIGS. 1D-1F, the reference potential, V_{REF}, is applied by each of DC2 and DC4 to the electrically conductive pad pairs 220C/220C' and 220D/220D' respectively, and a potential −XV, less than V_{REF}, is applied by each of DC1 and DC3 to the electrically conductive pad pairs 220A/220A' and 220B/220B' respectively, so as to establish an electric field E2 which is parallel with the upstream edges 212C, 214C and the downstream edges 212D, 214D of the circuit boards 212, 214, and which extends in a direction from and generally normal to the sides 212F, 212F toward and normal to the sides 212E, 214E of the circuit boards as depicted in FIG. 7B. With the electric field, E2, established as illustrated in FIG. 7B, ions 250 drifting through the drift tube segment 32_2 in the direction generally parallel with the ion travel axis 72 of the drift tube 12''' and entering the channel 216 through the upstream edges 212C, 214C of the ion steering channel 210 will be steered or guided (or directed) by the electric field, E2, so as to be diverted to travel in a direction from and generally normal to the sides 212F, 212F toward and normal to the sides 212E, 214E of the circuit boards and thus into the drift tube segment 34_1 of the multiple-pass drift tube 14'' as described above with respect to FIGS. 1D-1F. Thus, the ions drifting through the drift tube segment 32_2 in the direction generally parallel with the ion travel axis 72 of the drift tube 12''' are diverted by E2 to travel in a direction that is generally normal to the ion travel axis 72. Thereafter, as long as the voltage sources DC1-DC4 continue to be controlled so as to maintain the electric field E2, ions 270 drifting through the multiple-pass drift tube 14'' in a clockwise direction and generally parallel with the ion travel axis 70 of the multiple-pass drift tube 14'' (as viewed in FIG. 1D) will enter the channel 216 from the drift tube segment 34_2 at the sides 212F, 214F of the circuit boards 212, 214 and be steered or guided (or directed) by the electric field, E2, in a direction parallel with the ion travel axis 70 of the multiple-pass drift tube 14'' and thus back into the drift tube segment 34_1 as described above with respect to FIGS. 1D-1F.

After a desired number of traversals by the ions through the multiple-pass drift tube 14'', the reference potential, V_{REF} or other suitable reference potential, is applied by each of DC1 and DC2 to the electrically conductive pad pairs 220A/220A' and 220C/220C' respectively, and the potential −XV or other suitable potential less than V_{REF}, is applied by each of DC3 and DC4 to the electrically conductive pad pairs 220B/220B and 220D/220D' respectively, so as to reestablish the electric field E1, or to establish another electric field in the same direction as E1, such that ions 280 drifting through the drift tube segment 34_2 of the multiple-pass drift tube 14'' and into the ion steering channel 210 will be steered or guided (or directed) by such an electric field in the downstream direction of the ion travel axis 72 of the single-pass drift tube 12''' thus into the drift tube segment 32_3 of the single-pass drift tube 12''' as described above with respect to FIGS. 1D-1F. Thus, the ions 280 drifting through the drift tube segment 34_2 of the multiple-pass drift tube 14'' in the direction generally parallel with the ion travel axis 70 of the multiple-pass drift tube 14'' are diverted by E2 to travel in a direction that is generally normal to the ion travel axis 70 as illustrated in FIG. 7A.

In each of the embodiments 10, 10', 10'', 10''' of the hybrid ion mobility spectrometer illustrated in FIGS. 1A-1F, ion funnels, e.g., in the form of ion funnels 32_1-32_{11} and/or drift tube sections 50, are illustratively implemented in and along the single-pass drift tube 12, 12', 12'', 12''' as well as in and along the multiple-pass drift tube 14, 14', 14''. In some alternate embodiments, including any such embodiments which include one or more ion steering or guiding structures 200 and/or 200' and/or ion steering channels 210, one or more such ion funnels may be replaced by one or more conventional ion carpets of the general form illustrated in FIG. 8. Referring to FIG. 8, the illustrated ion carpet 300 is provided in the form of a planar structure 302, e.g., a circuit board or other electrically insulating or non-conductive plate, having a ring structure 304 with multiple, axially aligned, electrically conductive rings with progressively decreasing ring diameters formed on one major surface 306A thereof. In the embodiment illustrated in FIG. 8, the ring structure 304 includes a number of axially aligned, electrically conductive, concentric rings 308A, 308B, 308C . . . formed on one major surface 306 thereof with each successive ring 308A, 308B, 308C . . . reduced in diameter relative to the previous ring. Adjacent rings 308A, 308B, 308C . . . are radially separated from each other by electrically insulating or non-conductive ring areas 310A, 3106, 310C . . . of the planar structure 302. In embodiments in which the planar member 302 is a circuit board, the electrically conductive rings 308A, 308B, 308C are illustratively applied in a conventional manner on and to the major surface 306A of the circuit board 302 in the form of electrically conductive films or traces, e.g., copper, aluminum and/or other electrically conductive material. An ion passageway 312, e.g., in the form of a through-hole, having a central axis in common with each of the number of electrically conductive rings 308A, 308B, 308C . . . and electrically insulating or non-conductive areas 310A, 3106, 310C . . . of the planar structure 302 is defined through the planar structure 302. In the illustrated embodiment, six such electrically conductive rings are shown, although it will be understood that the planar structure 302 may include more or fewer such rings. Moreover, it will be understood that whereas the electrically conductive rings 308A, 308B, 308C . . . and electrically insulating or non-conductive areas 310A, 3106, 310C . . . of the planar structure 302 are illustrated in FIG. 8 as being concentric structures, alternate embodiments are contemplated in which such structures are non-concentric but closed structures. In any case, a conventional AC voltage source, e.g., a conventional RF voltage source, 316 is coupled through a capacitor network to each of the electrically conductive rings 308A, 308B, 308C . . . such that an RF voltage of a first phase, ϕ_1, is applied to odd-numbered (or even-numbered) ones of the rings 308A, 308B, 308C . . . and the same RF voltage of a second phase, ϕ_2, is applied to even-numbered (or odd-numbered) ones of the rings 308A, 308B, 308C . . . . In some embodiments, $\phi_1-\phi_2$ (or $\phi_2-\phi_1$)=180 degrees such that an opposite phase RF voltage is applied to adjacent ones of the rings 308A, 308B, 308C . . . of the ion carpet 300 as illustrated in FIG. 8. Generally, the ion carpet 300 illustratively operates functionally the same as ion funnels in that ions travelling toward the major surface 306A of the ion carpet 300 are focused radially inwardly by the RF voltages applied to the rings 308A, 308B, 308C . . . toward and through the central ion passageway 312. Accordingly, the ion carpet 300 may be used in place of any ion funnel structure described in connection with any of the embodiments **10**, **10'**, **10"**, **10'''** of the hybrid ion mobility spectrometer illustrated in FIGS. **1**A-**1**F.

Referring now to FIG. **9**, a portion of another embodiment of an ion steering or guiding structure **400** is shown in the form of an electrically insulating or non-conductive planar member **410**, e.g., a printed circuit board or the like, having an inner, major surface **410**A upon which a number of electrically conductive pads are formed. The planar circuit board **410** illustratively includes an upstream edge **410**C, a downstream edge **410**D opposite the upstream edge **410**C and two opposing side edges **410**E, **410**F joining the upstream and downstream edges **410**C, **410**D, wherein the edges **410**C, **410**D, **410**E, **410**F surround the inner, major surface **410**A and an opposite outer, major surface **410**B (see, e.g., FIG. **14**), and wherein the terms "upstream" and downstream" are as described above. In the illustrated embodiment, the planar circuit board has two sets of two substantially identical and spaced apart electrically conductive pads **402**A and **404**A are formed thereon. Along the upstream edge **410**C and spaced-apart between the side edges **410**E, **410**F a pair of square or rectangular electrically conductive pads **402**A, **404**A are formed on the inner, major surface **410**A of the planar circuit board **410**, and along the downstream edge **410**D and spaced-apart between the side edges **410**E, **410**F a pair of generally arcuate-shaped electrically conductive pads **402**B, **404**B are formed on the inner, major surface **410**A. Each square or rectangular pad **402**A, **404**A has a substantially planar upstream edge **402**A**1**, **404**A**1** respectively that is substantially parallel with the upstream edge **410**C of the planar circuit board **410**, and a substantially planar downstream edge **402**A**2**, **404**A**2** respectively that is substantially parallel with the planar upstream edge **402**A**1**, **404**A**1** respectively. Each arcuate-shaped pad **402**B, **404**B, in contrast, has a generally planar upstream edge **40261**, **404**B**1** respectively that is generally parallel with and spaced apart from the downstream edge **402**A**2**, **404**A**2** of the respective square or rectangular pad **402**A, **404**A, and a generally planar downstream edge **402**B**2**, **404**B**2** respectively that illustratively forms an acute angle with the respective upstream edge **402**B**1**, **404**B**1** such that the arcuate-shaped pads **402**B, **404**B generally diverge from one another as the pads **402**B, **404**B extend generally toward the downstream edge **410**D of the planar circuit board **410**. Each of the actuate shaped pads **402**B, **404**B is flanked along opposing side edges by electrically conductive pads **402**C, **402**D and **404**C, **404**D respectively, each of which defines an arcuate-shaped side edge that faces a respectively arcuate-shaped side edge of the electrically conductive pads **402**B, **404**B such that all such opposing arcuate shaped side edges are spaced-apart equidistantly along the lengths of the opposing sides of the electrically conductive pads **402**B, **404**B.

Like the ion steering and guiding structure **210** illustrated in FIG. **6**, the steering or guiding structure **400** illustratively includes a second planar circuit board **410** configured identically to the planar circuit board **410** just described and having identical spaced-apart electrically conductive pads **402**A-**402**D, **404**A-**404**D formed thereon. All such electrically conductive pads **402**A-**402**D, **404**A-**404**D of the two planar circuit boards **410** are juxtaposed over corresponding ones of the electrically conductive pads **402**A-**402**D, **404**A-**404**D when the inner, major surfaces **410**A of the two identical circuit boards **410** are spaced apart from and generally parallel with each other so that the inner, major surfaces **212**A and **214**A define a channel, e.g., similar or identical to the channel **216**, therebetween as illustrated in FIG. **6** and described above. In the description that follows, it will be understood that an ion steering channel formed with the planar circuit board **410** illustrated in FIG. **9** will necessarily include such a second, identically configured planar circuit board **410**, and that although only a single one of the planar circuit boards **410** is illustrated in FIGS. **9** and **10**A-**10**B, such a second planar circuit board **410** will be connected to voltage sources identically as shown and described with respect to the illustrated planar circuit board **410** and that the functional operation, e.g., relating to ion steering, of the ion steering channel formed with the illustrated planar circuit board **410** will generally take place in and through the channel formed between the illustrated circuit board **410** and such a second planar circuit board **410**.

In the embodiment illustrated in FIG. **9**, a first DC voltage source DC**1** is electrically connected to each of the juxtaposed electrically conductive pads **402**A (of the illustrated planar circuit board **410** and a second, identically configured planar circuit board spaced apart therefrom) such that the potential at both pads **402**A is the potential produced by DC**1**, a second DC voltage source DC**2** is electrically connected to each of the juxtaposed electrically conductive pads **404**A such that the potential at both pads **404**A is the potential produced by DC**2**, a third DC voltage source DC**3** is electrically connected to each of the juxtaposed electrically conductive pads **402**B such that the potential at both pads **402**B is the potential produced by DC**3**, a fourth DC voltage source DC**4** is electrically connected to each of the juxtaposed electrically conductive pad pairs **402**C, **402**D such that the potential at both pairs of pads **402**C, **402**D is the potential produced by DC**4**, a fifth DC voltage source DC**5** is electrically connected to each of the juxtaposed electrically conductive pads **404**B such that the potential at both pads **404**B is the potential produced by DC**5**, and a sixth DC voltage source DC**6** is electrically connected to each of the juxtaposed electrically conductive pad pairs **404**C, **404**D such that the potential at both pairs of pads **404**C, **404**D is the potential produced by DC**6**. In some embodiments, one or more conventional electrical components, e.g., resistors or other components, may be interconnected between one or more of the voltage sources DC**1**-DC**6** and one or more of the corresponding electrically conductive pads **402**A-**402**D, **404**A-**404**D and/or between two or more, and/or two or opposed pairs, of the electrically conductive pads **402**A-**402**D, **404**A-**404**D. In the illustrated embodiment, each of the DC voltage sources DC**1**-DC**6** is independently controlled, e.g., via manually or via the processor **42**, although in alternate embodiments two or more of the DC voltage sources DC**1**-DC**6** may be controlled together as a group. In any case, it will be understood that although the voltage sources DC**1**-DC**6** are illustrated and disclosed as being DC voltage sources, this disclosure contemplates other embodiments in which one or more of the voltage sources DC**1**-DC**6** is or includes an AC voltage source such as, for example, an RF voltage source suitably coupled, e.g., capacitively, via conventional electrical components to corresponding ones or pairs of the electrically conductive pads **402**A-**402**D, **404**A-**404**D.

Referring now to FIGS. **10**A and **10**B, operation of an ion steering channel **400**, formed by the planar circuit board **410** spaced apart from a second, identical planar circuit board **410** with corresponding ones of the electrically conductive pads **402**A-**402**D, **404**A-**404**D of each circuit board **410** juxtaposed with each other, will be described. The DC voltage sources DC**1**-DC**6** are omitted in FIGS. **10**A and **10**B for clarity of illustration, and instead the various DC voltages produced thereby and applied to the connected pairs of electrically conductive pads **402**A-**402**D, **404**A-**404**D are represented graphically. Referring specifically now to FIG. **10**A, the ion steering channel **400** is shown in a state in which a reference potential, VREF, is applied by DC**1** to the electrically conductive pad pairs **402**A and by DC**4** to the electrically conductive pad pairs **402**C and **402**D, and a potential −XV, less than VREF, is applied by DC**3** to the electrically conductive pad pairs **402**B. Illustratively, VREF may be any positive or negative voltage, or may be zero volts, e.g., ground potential, and −XV may be any voltage, positive, negative or zero voltage that is less than VREF so as to establish an electric field E**1** which is normal to the planar edges **402**A**1**, **402**A**2**, **402**B**1**, **402**B**2** of the electrically conductive pad pairs **402**A, **402**B respectively and which thus follows the arcuate shape of the electrically conductive pad pairs **402**B as shown. Because the potential applied by DC**4** to the electrically conductive pad pairs **402**C and **402**D is also VREF, additional electric fields, ES, are thus established normal to the arcuate side edges of the electrically conductive pad pairs **402**B in the direction of the electrically conductive pad pairs **402**B to thereby confine ions to the arcuate path defined by the electrically conductive pad pairs **402**B such that the ions entering the ion steering channel **400** at and in a direction normal to the upstream edges **410**C travel linearly across the electrically conductive pad pairs **402**A and then across the electrically conductive pad pairs **402**B generally in the arcuate direction defined by the arcuate electric field E**1**.

Referring specifically now to FIG. **10**B, the ion steering channel **400** is shown in a state in which a reference potential, VREF, is applied by DC**2** to the electrically conductive pad pairs **404**A and by DC**6** to the electrically conductive pad pairs **404**C and **404**D, and a potential −XV, less than VREF, is applied by DC**5** to the electrically conductive pad pairs **404**B. Illustratively, VREF may be any positive or negative voltage, or may be zero volts, e.g., ground potential, and −XV may be any voltage, positive, negative or zero voltage that is less than VREF so as to establish an electric field E**2** which is normal to the planar edges **404**A**1**, **404**A**2**, **404**B**1**, **404**B**2** of the electrically conductive pad pairs **404**A, **404**B respectively and which thus follows the arcuate shape of the electrically conductive pad pairs **404**B as shown. Because the potential applied by DC**6** to the electrically conductive pad pairs **404**C and **404**D is also VREF, additional electric fields, ES, are thus established normal to the arcuate side edges of the electrically conductive pad pairs **404**B in the direction of the electrically conductive pad pairs **404**B to thereby confine ions to the arcuate path defined by the electrically conductive pad pairs **404**B such that the ions entering the ion steering channel **400** at and in a direction normal to the upstream edges **410**C travel linearly across the electrically conductive pad pairs **404**A and then across the electrically conductive pad pairs **404**B generally in the arcuate direction defined by the arcuate electric field E**2**.

In the embodiment shown in FIG. **10**A, a potential +YV is illustratively applied by DC**2**, DC**5** and DC**6** to the electrically conductive pad pairs **404**A, **404**B and **404**C/**404**D respectively, and in the embodiment shown in FIG. **10**B the potential +YV is illustratively applied by DC**1**, DC**3** and DC**4** to the electrically conductive pad pairs **402**A, **402**B and **402**C/**402**D respectively. Illustratively, +YV is selected to establish a repulsive electric field ER of sufficient strength to confine ions entering the ion steering channel **400** at and in a direction normal to the upstream edges **410**C to the electrically conductive pad pairs **402**A and **404**B respectively so that such ions will not be lost and will be directed by the electric fields E**1** and E**2** respectively to follow the arcuate path established thereby. In some alternate embodiments, DC**2**, DC**5** and DC**6** may instead apply VREF to the electrically conductive pad pairs **404**A, **404**B and **404**C/**404**D respectively and/or DC**1**, DC**3** and DC**4** may instead apply VREF to the electrically conductive pad pairs **402**A, **402**B and **402**C/**402**D respectively.

As illustrated in FIGS. **10**A and **10**B, the ion steering channel **400** is selectively operable, via control of the voltage sources DC**1**-DC**6**, to direct ions entering the ion steering channel **400** at and in a direction normal to the upstream edges **410**C along the arcuate path established by E**1** or E**2**, wherein the ion outlets of the arcuate paths diverge from each other. In some embodiments, the ion steering channel **400** may be used in place of the ion gate pairs in any of the diverging drift tube segments of either of the embodiments **10**, **10'** illustrated in FIGS. **1**A and **1**B, e.g., in place of the ion gate pair G**1**, G**2** in the drift tube segment $\mathbf{36}_2$ of the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A, in place of the ion gate pair G**1**, G**2** in the drift tube segment $\mathbf{38}_1$ of the hybrid ion mobility spectrometer **10'** illustrated in FIG. **1**B and/or in place of the ion gate pair G**3**, G**4** in the drift tube segment $\mathbf{36}_2$ of the hybrid ion mobility spectrometer **10'**. Alternatively or additionally, the ion steering channel **400** illustrated in FIGS. **9**-**10**B may be rotated 180 degrees such that ions enter the ion steering channel **400** at and in a direction normal to the edges **410**D and the rotated ion steering channel **400** may be used in place of the ion gate G**3** in the drift tube segment $\mathbf{36}_1$ of the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A. In any such embodiment, the electrically conductive arcuate pad pairs **402**B-**402**D, **404**B-**404**D are illustratively shaped such that the curvatures of such pad pairs match and align with the curvatures of the diverging paths of the drift tube segments $\mathbf{36}_2$, $\mathbf{38}_1$ and/or of the converging paths of the drift tube segment $\mathbf{36}_1$.

In some embodiments in which either of the ion steering channel **210** and/or the ion steering channel **400** is implemented, it may be desirable to, under some operating conditions, selectively confine ion travel or passage to only one side or the other of the channel **210**, **400** and, under other operating conditions, to allow for ion travel through both sides of the channel **210**, **400**. As used herein, "through one side of the channel" will be understood to mean ion travel through the channel **210**, **400** along one axially or transversely aligned set of pairs of electrically conductive pads, e.g., axially along the aligned set of the electrically conductive pad pairs **402**A and **402**B under the influence of the electric field E**1** as illustrated in FIG. **10**A, axially along the aligned set of the electrically conductive pad pairs **404**A and **404**B under the influence of the electric field E**2** as illustrated in FIG. **10**B, transversely along the aligned set of electrically conductive pad pairs **220**C, **220**C' and **220**A, **220**A' as depicted by the dashed line **280** in FIG. **7**A, and axially along the aligned set of electrically conductive pad pairs **220**C, **220**C' and **220**D, **220**D' as depicted by the solid line **250** in FIG. **7**B. Similarly, "through both sides of the channel" will be understood to mean ion travel through the channel **210**, **400** along both axially or transversely aligned sets of pairs of electrically conductive pads, e.g., axially along the aligned sets of electrically conductive pad pairs **220**A, **220**A' and **220**B, **220**B' and, at the same time, axially along the aligned sets of electrically conductive pad pairs **220**C, **220**C' and **220**D, **220**D' as depicted by the solid line **230** in FIG. **7**A, and transversely along the aligned sets of electrically conductive pad pairs **220**C, **220**C' and **220**A, **220**A' and, at the same time, transversely along the aligned sets of electrically conductive pad pairs **220**D, **220**D' and **220**B, **220**B' as depicted by the dashed line **270** in FIG. 7B.

In some such embodiments, selective guidance or steering of ion travel or passage through only one side or the other, or through both sides, of an ion steering channel **210**, **400** is accomplished with a dual-passage or ion carpet, one example embodiment of which is illustrated by example in FIG. **11**. Referring now to FIG. **11**, the illustrated dual-passage ion carpet **500** is provided in the form of a planar structure **502**, e.g., a circuit board or other electrically insulating or non-conductive plate, having side-by-side ring structure **504**A, **504**B each with multiple, axially aligned and progressively smaller electrically conductive rings formed on one major surface **506**A thereof. In the illustrated embodiment, the planar circuit board **502** illustratively has a top edge **502**A, a bottom edge **502**B opposite the top edge **502**A with the top and bottom edges **502**A, **502**B joined by opposing edges **502**C, **502**D. The major surface **506**A of the circuit board is defined between the edges **502**A-**502**D on one side of the circuit board **502**, and another major surface **506**B (see, e.g., FIGS. **12**A-**13**) is defined between the edges **502**A-**502**D opposite the major surface **506**A.

In the embodiment illustrated in FIG. **11**, the ring structure **504**A includes a number of axially aligned, electrically conductive, elliptical rings **508**A, **508**B, **508**C . . . formed on the major surface **506**A of the circuit board **502** with each successive ring **508**A, **508**B, **508**C . . . reduced in length of both major and minor axes relative to the previous ring. Adjacent rings **508**A, **508**B, **508**C . . . are radially separated from each other by electrically insulating or non-conductive ring areas **510**A, **510**B, **510**C . . . of the planar structure **502**. An ion passageway **512**, e.g., in the form of a through-hole, having a central axis in common with each of the number of electrically conductive rings **508**A, **508**B, **508**C . . . and electrically insulating or non-conductive areas **510**A, **510**B, **510**C . . . of the planar structure **502** is defined through the planar structure **502**. Illustratively, the ring structure **504**A is positioned on the major surface **506**A of the circuit board **502** such that the ion passageway **512** aligns with the channel **216** or space defined between the opposed circuit boards of an ion steering channel **210**, **400** and is also centrally aligned with axially or transversely aligned with sets of pairs of electrically conductive pads formed on one side, e.g., a left side, of the ion steering channel **210**, **400** when the ion carpet **500** is operatively mounted to or operatively positioned adjacent to the ion steering channel **210**, **400**, e.g., such that the ion passageway **512** bisects or approximately bisects the channel **216** and bisects or approximately bisects the axially or transversely aligned sets of pairs of electrically conductive pads on one side of the ion steering channel. In the illustrated embodiment, 13 such electrically conductive rings are shown, although it will be understood that the planar structure **502** may include more or fewer such rings. Moreover, it will be understood that whereas the electrically conductive rings **508**A, **508**B, **508**C . . . and electrically insulating or non-conductive areas **510**A, **5106**, **510**C . . . of the planar structure **502** are illustrated in FIG. **11** as being elliptical structures, alternate embodiments are contemplated in which such structures are concentric or other closed structures. In any case, a conventional AC voltage source **516**, e.g., a conventional RF voltage source, is operatively coupled through a capacitor network to each of the electrically conductive rings **508**A, **508**B, **508**C . . . such that an RF voltage of a first phase, ϕ_1, is applied to odd-numbered (or even-numbered) ones of the rings **508**A, **508**B, **508**C . . . and the same RF voltage of a second phase, ϕ_2, is applied to even-numbered (or odd-numbered) ones of the rings **508**A, **508**B, **508**C . . . . In some embodiments, $\phi_1-\phi_2$ (or $\phi_2-\phi_1$)=180 degrees such that an opposite phase RF voltage is applied to adjacent ones of the rings **508**A, **508**B, **508**C . . . of the ion carpet **500**.

The ring structure **504**B of the ion carpet **500** likewise includes a number of axially aligned, electrically conductive, elliptical rings **528**A, **528**B, **528**C . . . formed on the major surface **506**A of the circuit board **502** with each successive ring **528**A, **528**B, **528**C . . . reduced in length of both major and minor axes relative to the previous ring. Adjacent rings **528**A, **528**B, **528**C . . . are radially separated from each other by electrically insulating or non-conductive ring areas **530**A, **530**B, **530**C . . . of the planar structure **502**. An ion passageway **532**, e.g., in the form of a through-hole, having a central axis in common with each of the number of electrically conductive rings **528**A, **528**B, **528**C . . . and electrically insulating or non-conductive areas **530**A, **530**B, **530**C . . . of the planar structure **502** is defined through the planar structure **502**. Illustratively, the ring structure **504**B is positioned on the major surface **506**A of the circuit board **502** such that the ion passageway **532** aligns with the channel **216** or space defined between the opposed circuit boards of an ion steering channel **210**, **400** and is also centrally aligned with axially or transversely aligned with sets of pairs of electrically conductive pads formed on the other side (relative to the ion passageway **512**), e.g., a right side, of the ion steering channel **210**, **400** when the ion carpet **500** is operatively mounted to or operatively positioned adjacent to the ion steering channel **210**, **400**, e.g., such that the ion passageway **532** bisects or approximately bisects the channel **216** and bisects or approximately bisects the axially or transversely aligned sets of pairs of electrically conductive pads on the side of the ion steering channel opposite that with which the ion passageway **512** is aligned. In the illustrated embodiment the ring structure **504**B is identical to the ring structure **504**A such that it includes **13** electrically conductive and elliptically shaped rings, although it will be understood that the ring structure **504**B may be different from the ring structure **504**A by having more or fewer such rings and/or by having rings of other shapes. In embodiments in which the planar member **502** is a circuit board, the electrically conductive rings **508**A, **508**B, **508**C . . . and **528**A, **528**B, **528**C . . . are illustratively applied in a conventional manner on and to the major surface **506**A of the circuit board **502** in the form of electrically conductive films or traces, e.g., copper, aluminum and/or other electrically conductive material.

In any case, a conventional AC voltage source **536**, e.g., a conventional RF voltage source, is operatively coupled through a capacitor network to each of the electrically conductive rings **528**A, **528**B, **528**C . . . such that an RF voltage of a first phase, ϕ_1, is applied to odd-numbered (or even-numbered) ones of the rings **528**A, **528**B, **528**C . . . and the same RF voltage of a second phase, ϕ_2, is applied to even-numbered (or odd-numbered) ones of the rings **528**A, **528**B, **528**C . . . . In some embodiments, $\phi_1-\phi_2$ (or $\phi_2-\phi_1$)= 180 degrees such that an opposite phase RF voltage is applied to adjacent ones of the rings **528**A, **528**B, **528**C . . . of the ion carpet **500**.

Generally, the ring structures **504**A, **504**B of the ion carpet **500** are selectively controllable, together or each independently of the other, to operate as described above with respect to the ion carpet **300** illustrated in FIG. **8**. In some embodiments and/or under some operating conditions in which it is desired to focus and pass ions through both ion passageways **512**, **532**, the ring structures **504**A and **504**B are controlled via the voltage sources **516** and **532** such that some of the ions travelling toward the major surface **506**A of the ion carpet **500** are focused radially inwardly by the RF voltages applied by the voltage source **516** to the ring structure **504**A toward and through the central ion passageway **512** and others of the ions travelling toward the major surface **506**A of the ion carpet **500** are focused radially inwardly by the RF voltages applied by the voltage source **536** to the ring structure **504**B toward and through the central ion passageway **532**. In other embodiments and/or under other operating conditions in which it is desired to focus and pass ions only through the ion passageway **512**, the ring structure **504**A is controlled via the voltage source **516** such that ions travelling toward the major surface **506**A of the ion carpet **500** are focused radially inwardly by the RF voltages applied by the voltage source **516** to the ring structure **504**A toward and through the central ion passageway **512**, and the voltage source **536** is either not activated so that ions traveling toward the major surface **506**A of the ion carpet **500** are not radially focused relative to the ring structure **504**B and therefore generally do not pass through the central ion passageway **532**, or is activated and controlled in a manner that does not cause ions traveling toward the major surface **506**A of the ion carpet to be radially focused relative to the ring structure **504**B and therefore generally does not provide for the passage of ions through the central ion passageway **532**. In still other embodiments and/or under still other operating conditions in which it is desired to focus and pass ions only through the ion passageway **532**, the ring structure **504**B is controlled via the voltage source **536** such that ions travelling toward the major surface **506**A of the ion carpet **500** are focused radially inwardly by the RF voltages applied by the voltage source **536** to the ring structure **504**B toward and through the central ion passageway **532**, and the voltage source **516** is either not activated so that ions traveling toward the major surface **506**A of the ion carpet **500** are not radially focused relative to the ring structure **504**A and therefore generally do not pass through the central ion passageway **512**, or is activated and controlled in a manner that does not cause ions traveling toward the major surface **506**A of the ion carpet to be radially focused relative to the ring structure **504**A and therefore generally does not provide for the passage of ions through the central ion passageway **512**. Accordingly, the ion carpet **500** may be used in combination with any of the ion gates G**1**-G**4** and/or with any ion steering channel **210**, **400** implemented in any of the embodiments **10**, **10'**, **10"**, **10'"** of the hybrid ion mobility spectrometer illustrated in FIGS. **1**A-**1**F.

Referring now to FIG. **12**A, an example embodiment is shown of a portion of the hybrid ion mobility spectrometer **10** or **10'** in which the ion funnel $\mathbf{32}_5$ and the ion gates G**1**, G**2** (FIG. **1**A) or G**3**, G**4** (FIG. **1**B) positioned in the drift tube section $\mathbf{36}_2$ are replaced by an ion carpet **500** coupled to the upstream end of an ion steering channel **400**. The ion carpet **500** is illustratively positioned such that the central ion passageway **512** of the ring structure **504**A bisects or approximately bisects the space between the planar circuit boards **410** and axially bisects or approximately bisects the electrically conductive pad pairs **404**A at the upstream edge **410**C of the ion steering channel **400**, and that the central ion passageway **532** of the ring structure **504**B bisects or approximately bisects the space between the planar circuit boards **410** and axially bisects or approximately bisects the electrically conductive pad pairs **402**A at the upstream edge **410**C of the ion steering channel **400**. Although not shown in FIG. **12**A, it will be understood that the voltage sources DC**1**-DC**6** are operatively connected to the electrically conductive pad pairs **402**A-**402**D, **404**A-**404**D as illustrated in FIG. **9** and described above.

When it is desired to direct ions from the drift tube section $\mathbf{36}_1$ into the upper arm of the drift tube section $\mathbf{36}_2$, the voltage sources **516** and **536** are controlled, as described above, so that ions drifting through the drift tube section $\mathbf{36}_1$ toward the major surface **506**A of the ion carpet **500** pass through only the ion passageway **512** defined centrally through the ring structure **504**A. The voltage sources DC**1**-DC**4** and DC**6** are set to VREF and DC**5** is set to −XV so as to establish the electric field E**2** between the electrically conductive pad pairs **404**A and **404**B as illustrated in FIG. **10**B. Thus as ions drift through the drift tube section $\mathbf{36}_1$ toward the major surface **506**A of the ion carpet **500**, such ions are radially focused by the ring structure **504**A and pass through the ion passageway **512** thereof where such ions are then steered or guided by the electric field E**2** toward and into the upper arm of the drift tube section $\mathbf{36}_2$.

When it is desired to direct ions from the drift tube section $\mathbf{36}_1$ into the lower arm of the drift tube section $\mathbf{36}_2$, the voltage sources **516** and **536** are controlled, as described above, so that ions drifting through the drift tube section $\mathbf{36}_1$ toward the major surface **506**A of the ion carpet **500** pass through only the ion passageway **532** defined centrally through the ring structure **504**B. The voltage sources DC**1**, DC**2** and DC**4**-DC**6** are set to VREF and DC**3** is set to −XV so as to establish the electric field E**1** between the electrically conductive pad pairs **402**A and **402**B as illustrated in FIG. **10**A. Thus as ions drift through the drift tube section $\mathbf{36}_1$ toward the major surface **506**A of the ion carpet **500**, such ions are radially focused by the ring structure **504**B and pass through the ion passageway **532** where such ions are then steered or guided by the electric field E**1** toward and into the lower arm of the drift tube section $\mathbf{36}_2$.

Referring now to FIG. **12**B, an example embodiment is shown of a portion of the hybrid ion mobility spectrometer **10** in which the ion funnel $\mathbf{32}_5$ and the ion gate G**3** positioned in the drift tube section $\mathbf{36}_1$ are replaced by an ion carpet **500** coupled to the downstream end of an ion steering channel **400** rotated 180 degrees relative to the configuration illustrated in FIGS. **9**-**10**A. The ion carpet **500** is illustratively positioned such that the central ion passageway **512** of the ring structure **504**A bisects or approximately bisects the space between the planar circuit boards **410** and axially bisects or approximately bisects the electrically conductive pad pairs **404**A at the (now) downstream edge **410**C of the ion steering channel **400**, and that the central ion passageway **532** of the ring structure **504**B bisects or approximately bisects the space between the planar circuit boards **410** and axially bisects or approximately bisects the electrically conductive pad pairs **402**A at the (now) downstream edge **410**C of the ion steering channel **400**. Although not shown in FIG. **12**B, it will be understood that the voltage sources DC**1**-DC**6** are operatively connected to the electrically conductive pad pairs **402**A-**402**D, **404**A-**404**D as illustrated in FIG. **9** and described above.

When it is desired to direct ions from the upper arm of the drift tube section $\mathbf{36}_1$ into the drift tube section $\mathbf{36}_2$, the voltage sources DC**1** and DC**3**-DC**6** are set to VREF and DC**2** is set to −XV so as to establish an electric field E**3** between the electrically conductive pad pairs **404**B, **404**C, **404**D and **404**B in the direction of the ion carpet **500**. The voltage sources **516** and **536** are controlled, as described above, so that ions being steered or guided by the electric field E**3** toward the major surface **506**A of the ion carpet **500** are radially focused by the ring structure **504**A and pass through only the ion passageway **512** defined centrally through the ring structure **504**A. Thus as ions drift through and along the upper arm of the drift tube section $\mathbf{36}_1$ toward the ion steering channel **400**, such ions are steered or guided by the electric field E**3** toward the ring structure **504**A defined on the major surface **506**A of the ion carpet **500**, and such ions are then radially focused by the ring structure **504**A and pass through the ion passageway **512** thereof and into the drift tube section $\mathbf{36}_2$.

When it is desired to direct ions from the lower arm of the drift tube section $\mathbf{36}_1$ into the drift tube section $\mathbf{36}_2$, the voltage sources DC**2**-DC**6** are set to VREF and DC**1** is set to −XV so as to establish an electric field E**4** between the electrically conductive pad pairs **402**B, **402**C, **402**D and **402**B in the direction of the ion carpet **500**. The voltage sources **516** and **536** are controlled, as described above, so that ions being steered or guided by the electric field E**4** toward the major surface **506**A of the ion carpet **500** are radially focused by the ring structure **504**B and pass through only the ion passageway **532** defined centrally through the ring structure **504**B. Thus as ions drift through and along the lower arm of the drift tube section $\mathbf{36}_1$ toward the ion steering channel **400**, such ions are steered or guided by the electric field E**4** toward the ring structure **504**B defined on the major surface **506**A of the ion carpet **500**, and such ions are then radially focused by the ring structure **504**B and pass through the ion passageway **532** thereof and into the drift tube section $\mathbf{36}_2$.

In some alternate embodiments of the structure illustrated in FIG. **12**B, the ion carpet **500** may be replaced by an ion carpet **300** positioned in the upper arm of the drift tube section $\mathbf{36}_1$ and spaced apart from or positioned adjacent to the ion entrance end of the electrically conductive pad pairs **404**B, and another ion carpet **300** positioned in the lower arm of the drift tube section $\mathbf{36}_1$ and spaced apart from or positioned adjacent to the ion entrance end of the electrically conductive pad pairs **402**B. Such ion carpets **300** may illustratively be controlled similarly as just described with respect to the ion carpet **500** to selectively guide ions from the upper or lower arms of the drift tube section $\mathbf{36}_1$ into the drift tube section $\mathbf{36}_2$.

In other alternate embodiments of the hybrid ion mobility spectrometer **10** illustrated in FIG. **1**A, some the structures illustrated in FIGS. **12**A and **12**B may be combined to replace the ion funnel $\mathbf{32}_5$ and the ion gates G**1**-G**3**. In one example, the ion steering channels **400** illustrated in FIGS. **12**A and **12**B may be positioned adjacent to each other with an ion carpet **500** positioned therebetween. In another example, the ion steering channels **400** illustrated in FIGS. **12**A and **12**B may be positioned adjacent to each other, e.g., in cascaded relationship, and individual ion carpets **300** may be positioned in the upper and lower arms of the drift tube segment $\mathbf{36}_1$ and/or in the upper and lower arms of the drift tube segment $\mathbf{36}_2$. Those skilled in the art will recognize other combinations of one or more ion steering channels **400** and one or more ion carpets **300** and/or one or more ion carpets **500** that may replace one or more corresponding ion funnels, ion gates and/or ion gate combinations in any of the hybrid ion mobility spectrometer embodiments **10**, **10'**, **10''**, **10'''** described herein and/or in any other conventional ion separation instrument, and it will be understood that this disclosure contemplates any such other combinations.

Referring now to FIG. **13**, an example embodiment is shown of a portion of the hybrid ion mobility spectrometer **10'''** in which the ion transition region **80** is replaced by an ion transition region **600** including a combination of an ion steering channel **210**, two ion carpets $\mathbf{500}_1$, $\mathbf{500}_2$ and two ion carpets $\mathbf{300}_1$, $\mathbf{300}_2$. The ion steering channel **210** is illustratively arranged as illustrated in FIG. **6** and with the upstream edges **212**C, **214**C of the circuit boards **212**, **214** at or adjacent the ion outlet end of the drift tube section $\mathbf{30}_4$, with the downstream edges **212**D, **214**D at or adjacent to the ion inlet end of the drift tube section $\mathbf{30}_6$, with the side edges **212**E, **214**E at or adjacent to the ion inlet end of the drift tube section $\mathbf{34}_1$ and with the side edges **212**F, **214**F at or adjacent to the ion outlet end of the drift tube section $\mathbf{34}_2$ (only the edges **212**C, **212**D, **212**E, **212**F of the circuit board **212** depicted in the top plan view illustrated in FIG. **13**). An ion carpet $\mathbf{500}_1$ is illustratively positioned at or adjacent to the upstream edges **212**C, **214**C of the ion steering channel **210** such that the major surface **506**A thereof having the ring structures **504**A, **504**B formed thereon faces away from the ion steering channel **210**, and another ion carpet $\mathbf{500}_2$ is illustratively positioned at or adjacent to the side edges **212**F, **214**F of the ion steering channel **210** such that the major surface **506**A thereof having the ring structures **504**A, **504**B formed therein faces away from the ion steering channel **210**. An ion carpet $\mathbf{300}_1$ is illustratively positioned in the drift tube section $\mathbf{30}_6$ with the major surface **306**A thereof having the ring structure **304** formed thereon facing the ion steering channel **210** and illustratively spaced apart from the downstream edges **212**D, **214**D by a distance D**3**, and another ion carpet $\mathbf{300}_2$ is illustratively positioned in the drift tube section $\mathbf{34}_1$ with the major surface **306**A thereof having the ring structure **304** formed thereon facing the ion steering channel **210** and illustratively spaced apart from the side edges **212**E, **214**E by a distance D**4**. The ion carpets $\mathbf{300}_1$, $\mathbf{300}_2$ are each illustratively positioned such that the central passageway **312** of the ring structure **304** bisects or approximately bisects the channel **216** of the ion steering channel **210** and centrally bisects or approximately bisects the circuit boards **212**, **214**. The ion carpets $\mathbf{500}_1$, $\mathbf{500}_2$ are illustratively positioned such that the central ion passageways **512**, **532** of the ring structures **504**A, **504**B respectively bisect or approximately bisect the channel **216** of the ion steering channel **210**. The ion carpet $\mathbf{500}_1$ is further illustratively positioned such that the central ion passageway **512** of the ring structure **504**A bisects or approximately bisects the aligned electrically conductive pad pairs **220**A, **220**A' and **220**B, **200**B' at the upstream edge **212**C, **214**C of the ion steering channel **210**, and that the central ion passageway **532** of the ring structure **504**B bisects or approximately bisects the aligned electrically conductive pad pairs **220**C, **220**C' and **220**D, **200**D' at the upstream edge **212**C, **214**C of the ion steering channel **210** (only the electrically conductive pads **220**A-**220**D of the circuit board **212** are depicted in dashed-line in the top plan view illustrated in FIG. **13**). The ion carpet $\mathbf{500}_2$ is further illustratively positioned such that the central ion passageway **512** of the ring structure **504**A bisects or approximately bisects the aligned electrically conductive pad pairs **220**C, **220**C' and **220**A, **200**A' at the side edge **212**F, **214**F of the ion steering channel **210**, and that the central ion passageway **532** of the ring structure **504**B bisects or approximately bisects the aligned electrically conductive pad pairs **220**D, **220**D' and **220**B, **200**B' at the side edge **212**E, **214**E of the ion steering channel **210**. Although not shown in FIG. **13**, it will be understood that the voltage sources DC**1**-DC**4** are operatively connected to the electrically conductive pad pairs **220**A/**220**A', **2206**/**2206'**, **220**C/**220**C' and **220**D/**220**D' as illustrated in FIG. **6** and described above.

When it is desired to axially pass ions from the drift tube section $\mathbf{30}_4$ into the drift tube section $\mathbf{30}_6$, the voltage sources DC**1** and DC**2** are set to VREF and the voltage sources DC3 and DC4 are set to −XV so as to establish the electric field E1 between the aligned electrically conductive pad pairs 220A, 220A' and 220B, 220B' and between the aligned electrically conductive pad pairs 220C, 220C' and 220D, 220D' in the axial direction of the drift tube sections 30_4 and 30_6. The voltage sources 516 and 536 for the ion carpet 500_1 are controlled, as described above, so that ions drifting through the drift tube section 30_1 toward the major surface 506A of the ion carpet 500_1 are radially focused by both ring structures 504A and 504B and therefore pass through both of the ion passageways 512, 532 defined centrally through the ring structures 504A, 504B respectively. Thus as ions drift through and along the drift tube section 30_4, such ions are radially focused by the ring structures 504A, 504B of the ion carpet 500_1 and pass in separate focused ion streams through the ion passageways 512, 532 respectively whereupon the focused ion stream exiting the ion passageway 512 is steered or guided by the electric field E1 established between the electrically conductive pad pairs 220A, 220A' and 220B, 220B' into the drift tube section 30_6 and the focused ion stream exiting the ion passageway 532 is likewise steered or guided by the electric field E1 established between the electrically conductive pad pairs 220C, 220C' and 220D, 220D' into the drift tube section 30_6. As the two separate focused ion streams drift through the distance D3 of the drift tube section 30_6 and toward the ion carpet 300_2, they are radially focused by the ring structure 304 of the ion carpet 300_2 into a single, combined ion stream to pass through the ion passageway 312 of the ion carpet 300_2 which ion passageway 312 is illustratively axially aligned with the ion travel axis 72 of the single-pass drift tube 12''' illustrated in FIG. 1E and described above. Illustratively, the distance D3 is selected so allow the two separate focused ion streams exiting the ion steering channel 210 to be combined and radially focused into a single focused ion stream to pass through the passageway 312 of the ion carpet 300_2.

When it is desired to transversely pass ions from the drift tube section 30_4 of the single-pass drift tube 12''' into the drift tube section 34_1 of the multiple-pass drift tube 14" illustrated in FIGS. 1D and 1E, the voltage sources DC2 and DC4 are set to VREF and the voltage sources DC1 and DC3 are set to −XV so as to establish the electric field E2 between the aligned electrically conductive pad pairs 220C, 220C' and 220A, 220A' and between the aligned electrically conductive pad pairs 220D, 220D' and 220B, 220B' in the axial direction of the drift tube sections 34_1 and 34_2. The voltage sources 516 and 536 for the ion carpet 500_1 are controlled, as described above, so that ions drifting through the drift tube section 30_1 toward the major surface 506A of the ion carpet 500_1 are radially focused only by the ring structure 504B and therefore pass only through the ion passageways 532 defined centrally through the ring structure 504B. As ions drift through and along the drift tube section 30_4 and are radially focused only by the ring structure 504B of the ion carpet 500_1, such ions pass in a single focused ion stream through the ion passageway 532 in a direction generally parallel with the ion travel axis 72 of the single-pass drift tube 12''' toward the aligned electrically conductive pads 220C, 220C' and 220D, 220D'. As the focused ion stream exits the ion passageway 532, however, it is steered or guided by the electric field E2 established between the electrically conductive pad pairs 220C, 220C' and 220A, 220A' and between the electrically conductive pad pairs 220D, 220D' and 220B, 220B' to change directions by approximately 90 degrees so as to pass into the drift tube section 34_1 of the multiple-pass drift tube 14". As the redirected ions drift through the distance D4 of the drift tube section 34_1 and toward the ion carpet 300_1, they are radially focused by the ring structure 304 of the ion carpet 300_1 so as to pass through the ion passageway 312 of the ion carpet 300_1 which ion passageway 312 is illustratively axially aligned with the ion travel axis 70 of the multiple-pass drift tube 14" illustrated in FIGS. 1E and 1F and described above. Illustratively, the distance D4 is selected so allow the two separate focused ion streams exiting the ion steering channel 210 to be combined and radially focused into a single focused ion stream to pass through the passageway 312 of the ion carpet 300_1.

As described above, the multiple-pass drift tube 14" is illustratively controlled to allow ions to travel therethrough any number of times, and in so doing the voltage sources DC1 and DC2 are the voltage sources DC2 and DC4 are maintained at VREF and the voltage sources DC1 and DC3 are maintained at −XV so as to maintain the electric field E2 between the aligned electrically conductive pad pairs 220C, 220C' and 220A, 220A' and between the aligned electrically conductive pad pairs 220D, 220D' and 220B, 220B' in the axial direction of the drift tube sections 34_1 and 34_2. The voltage sources 516 and 536 for the ion carpet 500_2 are controlled, as described above, so that ions drifting through the drift tube section 34_2 toward the major surface 506A of the ion carpet 500_2 are radially focused by both ring structures 504A and 504B and therefore pass through both of the ion passageways 512, 532 defined centrally through the ring structures 504A, 504B respectively. Thus as ions drift through and along the drift tube section 34_2, such ions are radially focused by the ring structures 504A, 504B of the ion carpet 500_2 and pass in separate focused ion streams through the ion passageways 512, 532 respectively whereupon the focused ion stream exiting the ion passageway 512 is steered or guided by the electric field E2 established between the electrically conductive pad pairs 220C, 220C' and 220A, 220A' into the drift tube section 34_1 and the focused ion stream exiting the ion passageway 532 is likewise steered or guided by the electric field E2 established between the electrically conductive pad pairs 220D, 220D' and 220E, 220E' into the drift tube section 34_1. As the two separate focused ion streams drift through the distance D4 of the drift tube section 34_1 and toward the ion carpet 300_1, they are radially focused by the ring structure 304 of the ion carpet 300_1 into a single, combined ion stream to pass through the ion passageway 312 of the ion carpet 300_1 which passageway 312 is illustratively axially aligned with the ion travel axis 70 of the multiple-pass drift tube 14" illustrated in FIG. 1D and described above.

When it is desired to transversely pass ions from the drift tube section 34_2 of the multiple-pass drift tube 14" into the drift tube section 30_6 of the single-pass drift tube 12''' illustrated in FIGS. 1D and 1E, e.g., after ions have circulated about the multiple-pass drift tube 14' a desired number of times, the voltage sources DC1 and DC2 are set to VREF and the voltage sources DC3 and DC4 are set to −XV so as to reestablish the electric field E1 between the aligned electrically conductive pad pairs 220A, 220A' and 220B, 220B' and between the aligned electrically conductive pad pairs 220C, 220C' and 220D, 220D' in the axial direction of the drift tube sections 30_4 and 30_6. The voltage sources 516 and 536 for the ion carpet 500_2 are illustratively controlled, as described above, so that ions drifting through the drift tube section 34_2 toward the major surface 506A of the ion carpet 500_2 are radially focused only by the ring structure 504A and therefore pass only through the ion passageway 516 defined centrally through the ring structure 504A. As ions drift through and along the drift tube section 34_2 and are radially focused only by the ring structure **504**A of the ion carpet 500_2, such ions pass in a single focused ion stream through the ion passageway **512** in a direction generally parallel with the ion travel axis **70** of the multiple-pass drift tube **14**" toward the aligned electrically conductive pads **220**C, **220**C' and **220**A, **220**A'. As the focused ion stream exits the ion passageway **512**, however, it is steered or guided by the electric field E**1** established between the electrically conductive pad pairs **220**C, **220**C' and **220**D, **220**D' and between the electrically conductive pad pairs **220**A, **220**A' and **220**B, **220**B' to change directions by approximately 90 degrees so as to pass into the drift tube section 30_6 of the single-pass drift tube **12**'". As the redirected ions drift through the distance D**3** of the drift tube section 30_6 and toward the ion carpet 300_2, they are radially focused by the ring structure **304** of the ion carpet 300_2 so as to pass through the ion passageway **312** of the ion carpet 300_2 which ion passageway **312** is, as described above, axially aligned with the ion travel axis **72** of the single-pass drift tube **12**'".

It will be understood that the embodiment illustrated in FIG. **13** represents only one non-limiting combination of the ion steering channel **210** and the ion carpets **300** and **500** implemented in the hybrid ion mobility spectrometer illustrated in FIGS. **1**D and **1**E, and that that other combinations which may include more or fewer ion carpets **300** and/or **500**, which may include additional ion steering channels **210** and/or which may include one or more of ion steering channels **400** are contemplated by this disclosure. As one specific and non-limiting example, the embodiment **600** illustrated in FIG. **13** may alternatively include one or more ion carpets **300** in place of either or both of the ion carpets **500**. As another non-limiting example, one or more of the ion carpets **300**, **500** may be omitted in favor one or more of the ion funnels illustrated in FIGS. **1**D and **1**E. Those skilled in the art will recognize other combinations of one or more ion steering channels **212** and one or more ion carpets **300** and/or one or more ion carpets **500** that may replace one or more corresponding ion funnels, ion gates and/or ion gate combinations in any of the hybrid ion mobility spectrometer embodiments **10**, **10**', **10**", **10**'" described herein and/or in any other conventional ion separation instrument, and it will be understood that this disclosure contemplates any such other combinations.

While the invention has been illustrated and described in detail in the foregoing drawings and description, the same is to be considered as illustrative and not restrictive in character, it being understood that only illustrative embodiments thereof have been shown and described and that all changes and modifications that come within the spirit of the invention are desired to be protected. For example, in some alternate embodiments, one or more conventional ion analytical instruments may be substituted for either or both of the ion source **18** and the ion detector **22** such that alternate and/or additional ion separation, ion conformation alteration, ion processing and/or ion analysis may be carried out on ions prior to entering and/or after exiting the single-pass drift tube **12**, **12**', **12**", **12**'". Alternatively or additionally, one or more conventional ion analytical instruments may be positioned within or interposed along either or both of the single-pass drift tube **12**, **12**', **12**", **12**'" and the multiple-pass drift tube **14**, **14**', **14**" such that alternate and/or additional ion separation, ion conformation alteration, ion processing and/or ion analysis may be carried out within or along the single-pass drift tube **12**, **12**', **12**", **12**'" and/or the multiple-pass drift tube **14**, **14**', **14**". In any case, examples of such conventional ion analytical instruments that precede the ion inlet **16** of the single-pass drift tube **12**, **12**', **12**", **12**'", that follow the ion outlet **20** of the single-pass drift tube **12**, **12**', **12**", **12**'" and/or that are positioned within or interposed along the single-pass drift tube **12**, **12**', **12**", **12**'" and/or the multiple-pass drift tube **14**, **14**', **14**" may include, but are not limited to, one or more drift tubes identical to or different from the single-pass drift tube **12**, **12**', **12**", **12**'" and/or the multiple-pass drift tube **14**, **14**', **14**", one or more mass analyzers and/or mass spectrometers, one or more liquid and/or gas chromatographs, one or mass filters (e.g., one or more multiple-pole mass filters), one or more collision cells and/or other ion fragmentation devices or regions, one or more ion activation regions in which an electric field is established that is high enough to alter the conformation of one or more ions but not high enough to fragment ions, or the like. It will be further understood that in embodiments that include two or more such conventional ion analytical instruments together, such two or more conventional ion analytical instruments may be positioned in parallel relative to each other, in series relative to each other (i.e., cascaded) or any combination of series and parallel.

Additionally or alternatively, those skilled in the art will recognize that the multiple-pass drift tube **14** illustrated in any of FIGS. **1**A-**1**B can, in some embodiments, be provided in the form of two or more series-connected and/or parallel-connected multiple-pass drift tubes. Alternatively or additionally still, such one or more multiple-pass drift tubes **14** can be augmented by one or more single-pass drift tubes **12** and/or by one or more conventional analytical instruments of the type described by example in the previous paragraph.

As another example, it will be understood that while the various embodiments of the hybrid ion mobility spectrometer **10**, **10**', **10**", **10**'" illustrated and described herein include a multiple-pass drift tube **14**, **14**', **14**" coupled to a single-pass drift tube **12**, **12**', **12**", **12**'" between an ion inlet **16** and an ion outlet **20** of the single-pass drift tube **12**, **12**', **12**", **12**'", this disclosure contemplates alternative embodiments in which the multiple-pass drift tube **14**, **14**', **14**" or other suitable multiple-pass drift tube is positioned upstream of the single-pass drift tube **12**, **12**', **12**", **12**'", i.e., prior to the ion inlet **16** and/or downstream of the single-pass drift tube **12**, **12**', **12**", **12**'", i.e., following the ion outlet **20**.

As still another example, operation of the ion gates G**1**-G**3** or G**1**-G**4** has been described herein in which such ion gates G**1**-G**3** or G**1**-G**4** are controlled to block or allow passage therethrough of some or all ions from a preceding, e.g. upstream, stage or section of the hybrid ion mobility spectrometer **10**, **10**', **10**", **10**'". It will be understood that this disclosure contemplates embodiments in which any one or more of the gates G**1**-G**3** or G**1**-G**4** may be controlled to intermediate positions, i.e., between their open and closed positions, to allow pass therethrough of only a fraction of the ions at any one or more times. This would allow, for example, operation of the single-pass drift tube **12**, **12**', **12**", **12**'" to be carried out simultaneously with the operation of the multiple-pass drift tube **14**, **14**', **14**" such that ions exiting more quickly from the single-pass drift tube **12**, **12**', **12**", **12**'" can be analyzed prior to analyzing ions exiting the multiple-pass drift tube.

What is claimed is:

1. An ion mobility spectrometer, comprising:

a first drift tube defining a closed path, the first drift tube responsive to application of at least a first voltage to establish a first electric field therein configured to cause ions within the first drift tube to move along and about the closed path while separating from one another as a function of ion mobility, and

means, coupled to opposed ends of the first drift tube to form part of the closed-path, for selectively passing ions into and out of the first drift tube.

2. The ion mobility spectrometer of claim 1, further comprising a second drift tube configured to supply the ions to the means for selectively passing ions into and out of the first drift tube.

3. The ion mobility spectrometer of claim 2, further comprising a third drift tube configured to pass therethrough ions exiting the means for selectively passing ions into and out of the first drift tube.

4. The ion mobility spectrometer of claim 3, wherein the second and third drift tubes together form respective portions of a linear drift tube responsive to application of at least a second voltage to establish a second electric field therein configured to cause ions therein to move along the linear drift tube while separating from one another as a function of ion mobility.

5. An ion mobility spectrometer, comprising:

a first drift tube responsive to application of at least a first voltage to establish a first electric field therein configured to cause ions within the first drift tube to move along and about the first drift tube while separating from one another as a function of ion mobility, and

a transition region coupled to opposed ends of the first drift tube such that the first drift tube and the transition region together define a closed path, the transition region responsive to application of at least a second voltage to cause the ions to move along and about the closed path, to application of at least a third voltage to selectively pass ions into the first drift tube and to application of at least a fourth voltage to selectively pass ions out of the first drift tube.

6. The ion mobility spectrometer of claim 5, further comprising a second drift tube coupled to an ion inlet of the transition region, the second drift tube responsive to at least a fifth voltage to supply ions to the transition region.

7. The ion mobility spectrometer of claim 6, further comprising a third drift tube coupled to an ion outlet of the transition region, the third drift tube responsive to at least a sixth voltage to pass therethrough ions exiting the transition region.

8. The ion mobility spectrometer of claim 5, wherein the transition region comprises:

a first planar circuit board having a plurality of electrically conductive pads formed thereon,

a second planar circuit board having a plurality of electrically conductive pads formed thereon, wherein the first and second circuit boards are spaced apart from one another to form an ion channel therebetween with the electrically conductive pads of each facing and juxtaposed with one another to form a plurality of pairs of juxtaposed pads, and

at least one voltage source operatively coupled to each of the electrically conductive pads of the first and second planar circuit boards, the at least one voltage source configured to selectively apply the at least the second voltage across at least one of the pairs of juxtaposed pads to establish an electric field therebetween configured to pass ions entering the ion channel from one of the opposed ends of the first drift tube into the other of the opposed ends of the first drift tube such that the ions move along and about the closed path, to selectively apply the at least the third voltage across at least one of the pairs of juxtaposed pads to establish an electric field therebetween configured to steer ions entering the ion channel from a source of ions into the first drift tube and to selectively apply the at least the fourth voltage across at least one of the pairs of juxtaposed pads to establish an electric field therebetween configured to steer ions entering the ion channel from the first drift tube out of and away from the first drift tube.

9. The ion mobility spectrometer of claim 8, further comprising a processor programmed to control the at least one voltage source to selectively apply the at least the second voltage in the form of a set of voltages across at least some of the plurality of pairs of juxtaposed pads to establish a corresponding set of electric fields in the ion channel configured to pass ions entering the ion channel from one of the opposed ends of the first drift tube into the other of the opposed ends of the first drift tube.

10. The ion mobility spectrometer of claim 9, further comprising a processor programmed to control the at least one voltage source to selectively apply the at least the third voltage in the form of a set of voltages across at least some of the plurality of pairs of juxtaposed pads to establish a corresponding set of electric fields in the ion channel configured to steer ions entering the ion channel from the source of ions into the first drift tube.

11. The ion mobility spectrometer of claim 10, wherein the processor is further programmed to control the at least one voltage source to selectively apply the at least a fourth voltage in the form of another set of voltages across at least some of the plurality of pairs of juxtaposed pads to establish a corresponding another set of electric fields in the ion channel configured to steer ions entering the ion channel from the first drift tube out of and away from the first drift tube.

12. The ion mobility spectrometer of claim 10, further comprising a second drift tube coupled to an ion inlet of the transition region, the second drift tube responsive to at least a fifth voltage to supply ions to the transition region,

wherein the processor is programmed to control the at least one voltage source to selectively apply the at least the third voltage in the form of the set of voltages across at least some of the plurality of pairs of juxtaposed pads to establish the set of electric fields in the ion channel configured to steer ions entering the ion channel from the second drift tube into the first drift tube.

13. The ion mobility spectrometer of claim 12, further comprising a third drift tube coupled to an ion outlet of the transition region, the third drift tube responsive to at least a sixth voltage to pass therethrough ions exiting the transition region, and

wherein the processor is programmed to control the at least one voltage source to selectively apply the at least the fourth voltage in the form of the another set of voltages across at least some of the plurality of pairs of juxtaposed pads to establish the another set of electric fields in the ion channel configured to steer ions entering the ion channel from the first drift tube into the third drift tube.

14. A method of operating an ion mobility spectrometer having a transition region coupled to opposed ends of a first drift tube such that the first drift tube and the transition region together define a closed path, wherein the first drift tube is responsive to application of at least a first voltage to establish an electric field therein configured to cause ions within the first drift tube to move through the first drift tube while separating from one another as a function of ion mobility, the method comprising:

selectively applying at least a second voltage to the transition region to cause the transition region to pass ions entering the transition region from a source of ions into the first drift tube,

selectively applying at least a third voltage to the transition region to cause the transition region to pass ions entering the transition region from one of the opposed ends of the first drift tube into the other of the opposed ends of the first drift tube such that the ions move along and about the closed path, and

after the ions in the first drift tube have traveled about the closed-path for at least a specified time period or at least a specified number of times, selectively applying at least a fourth voltage to the transition region to cause the transition region to pass at least some of the ions entering the transition region from the first drift tube out of and away from the first drift tube.

15. The method of claim **14**, wherein the ion mobility spectrometer further includes a second drift tube configured to supply the ions to the transition region,

and wherein selectively applying the at least a second voltage to the transition region establishes at least one electric field within the transition region configured to steer ions entering the transition region from the second drift tube into the first drift tube.

16. The method of claim **15**, wherein the ion mobility spectrometer further includes a second drift tube configured to pass therethrough ions exiting the transition region,

and wherein selectively applying the at least a fourth voltage to the transition region establishes at least one electric field within the transition region configured to steer ions entering the transition region from the first drift tube into the second drift tube.

17. The method of claim **14**, wherein the transition region comprises spaced apart planar circuit boards defining a plurality of electrically conductive pads on opposed surfaces of each so as to form an ion channel between the circuit boards with the electrically conductive pads of each of the circuit boards juxtaposed with one another to form a plurality of pairs of juxtaposed pads,

and wherein selectively applying the at least a third voltage to the transition region comprises selectively applying a set of voltages across at least some of the plurality of pairs of juxtaposed pads to establish a corresponding set of electric fields in the ion channel configured to steer ions entering the ion channel from a source of ions into the first drift tube.

18. The method of claim **17**, wherein the ion mobility spectrometer further includes a second drift tube coupled to an ion inlet of the transition region and configured to supply the ions to the transition region,

and wherein the set of electric fields established in the ion channel is configured to steer ions entering the ion channel from the second drift tube into the first drift tube.

19. The method of claim **14**, wherein the transition region comprises spaced apart planar circuit boards defining a plurality of electrically conductive pads on opposed surfaces of each so as to form an ion channel between the circuit boards with the electrically conductive pads of each of the circuit boards juxtaposed with one another to form a plurality of pairs of juxtaposed pads,

and wherein selectively applying the at least a fourth voltage to the transition region comprises selectively applying a set of voltages across at least some of the plurality of pairs of juxtaposed pads to establish a corresponding set of electric fields in the ion channel configured to steer ions entering the ion channel from the first drift tube out of and away from the first drift tube.

20. The method of claim **19**, wherein the ion mobility spectrometer further includes a second drift tube coupled to an ion outlet of the transition region and configured to pass therethrough ions exiting the transition region,

and wherein the set of electric fields established in the ion channel is configured to steer ions entering the ion channel from the first drift tube into the second drift tube.

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