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(54) **ION INJECTION INTO AN ELECTROSTATIC LINEAR ION TRAP USING ZENO PULSING**

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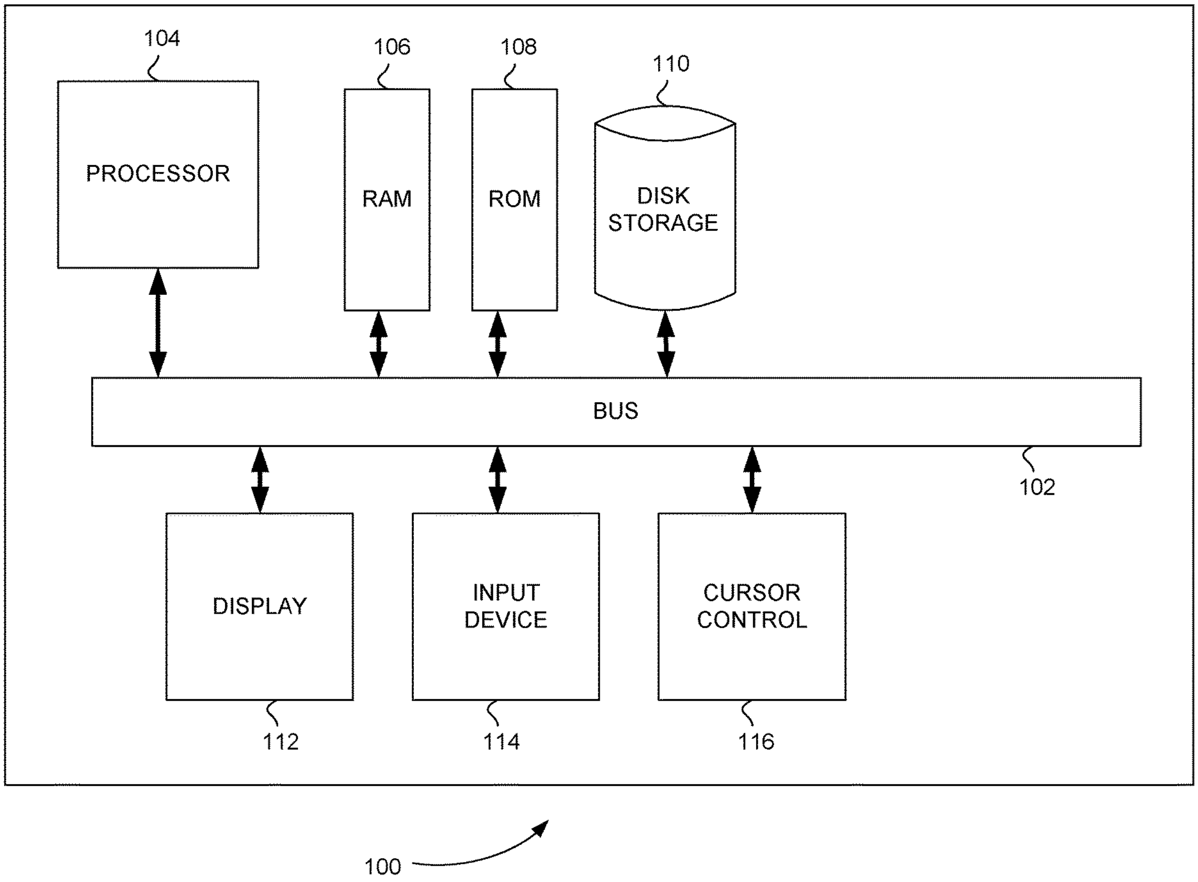
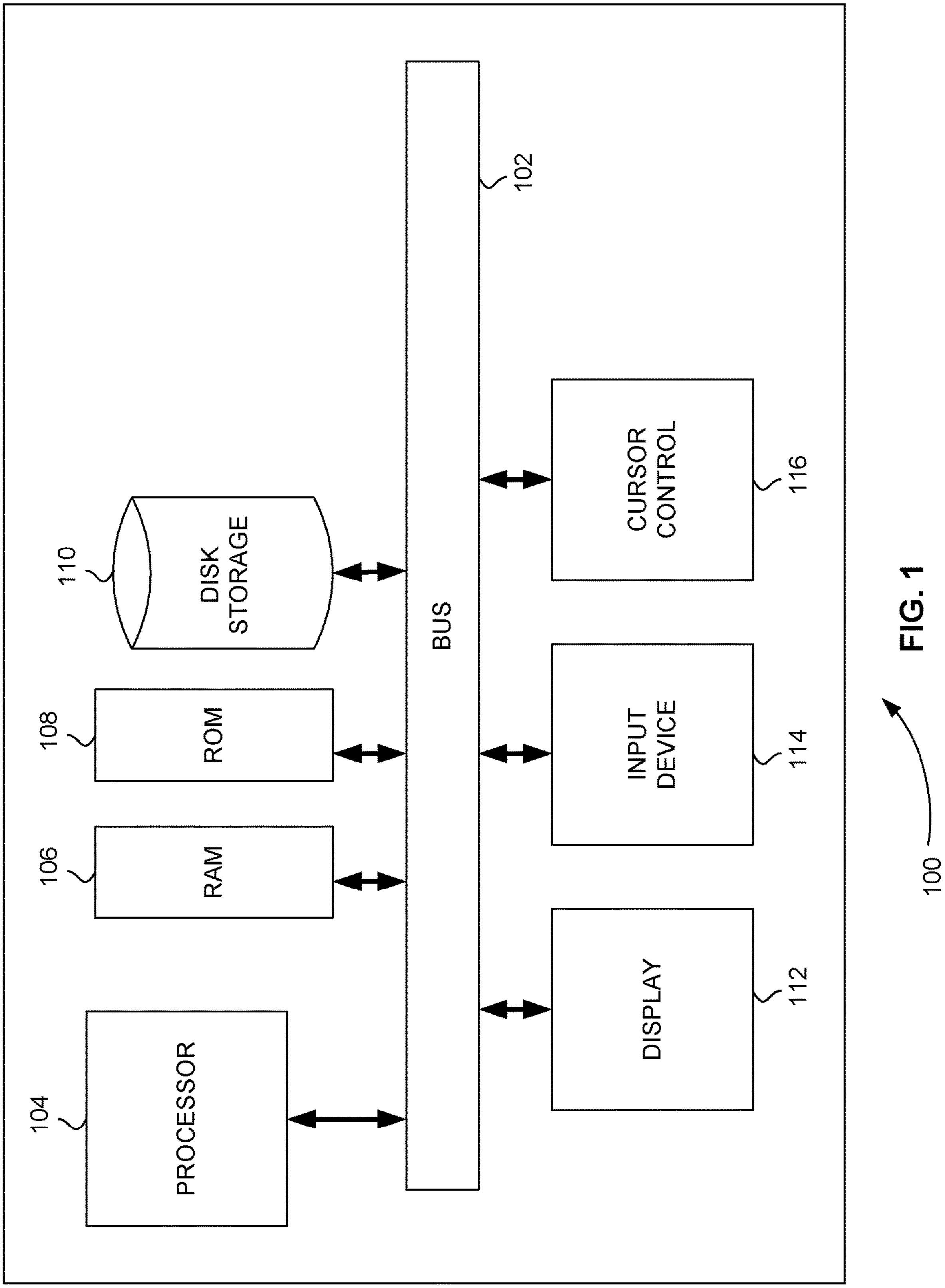
CPC ***H01J 49/4245*** (2013.01); ***H01J 49/0031*** (2013.01); ***H01J 49/426*** (2013.01)

(57) **ABSTRACT**

An ion guide defining a guide axis receives ions. The ion guide applies a potential profile that includes a pseudopotential well to the ions using an ion control field. The ion control field includes a component for restraining movement of the ions normal to the guide axis and a component for controlling the movement of the ions parallel to the guide axis. The ion guide sequentially injects the ions with the same ion energy and in decreasing order of m/z value into an ELIT aligned along an ELIT axis to focus the ions irrespective of m/z value at the same location on the ELIT axis within the ELIT at the same time by varying a magnitude of the pseudopotential well. The ELIT can trap the focused ions using in-trap potential lift or mirror-switching ion capture.





104
PROCESSOR
106
RAM
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DISK STORAGE
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INPUT DEVICE
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CURSOR CONTROL
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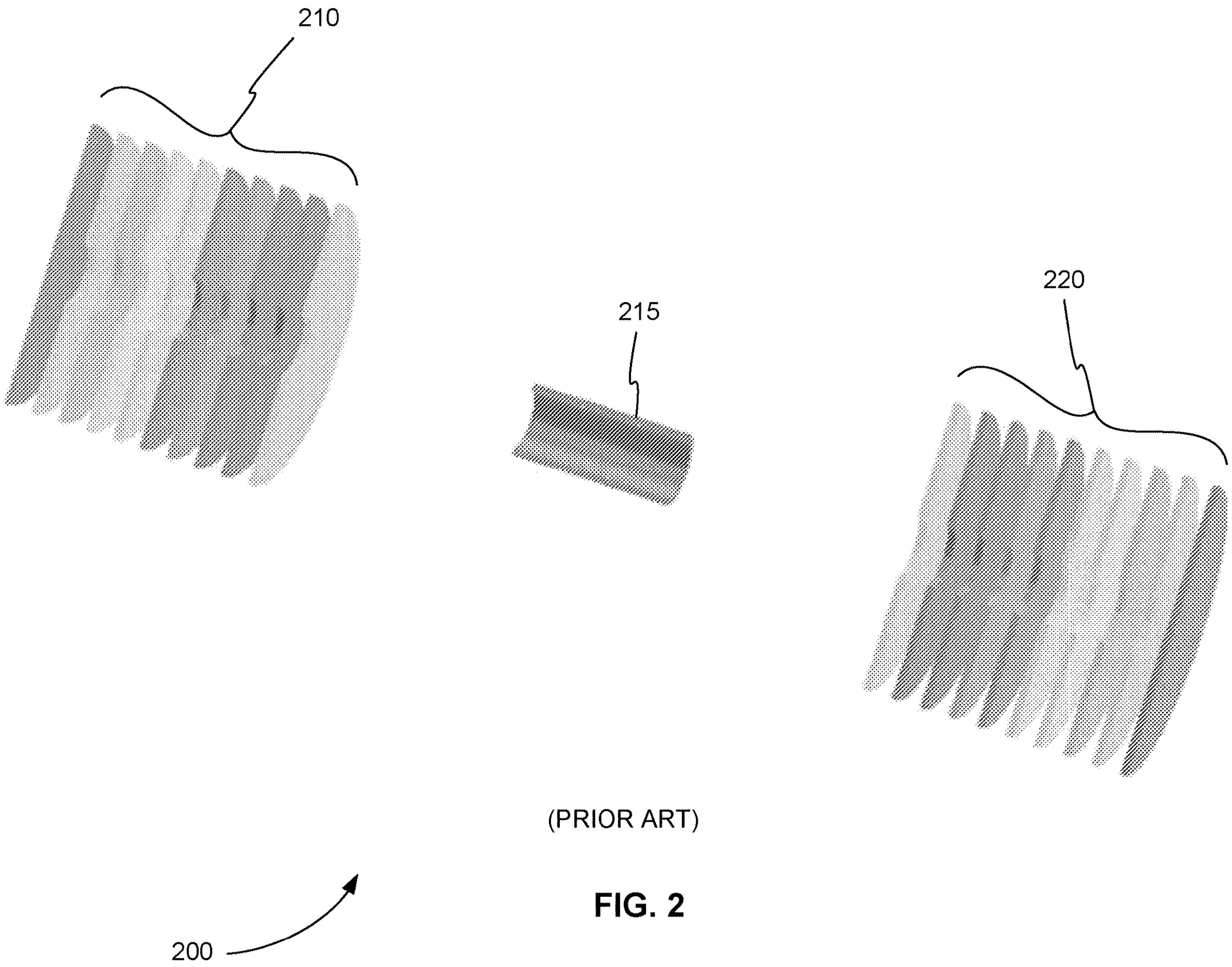
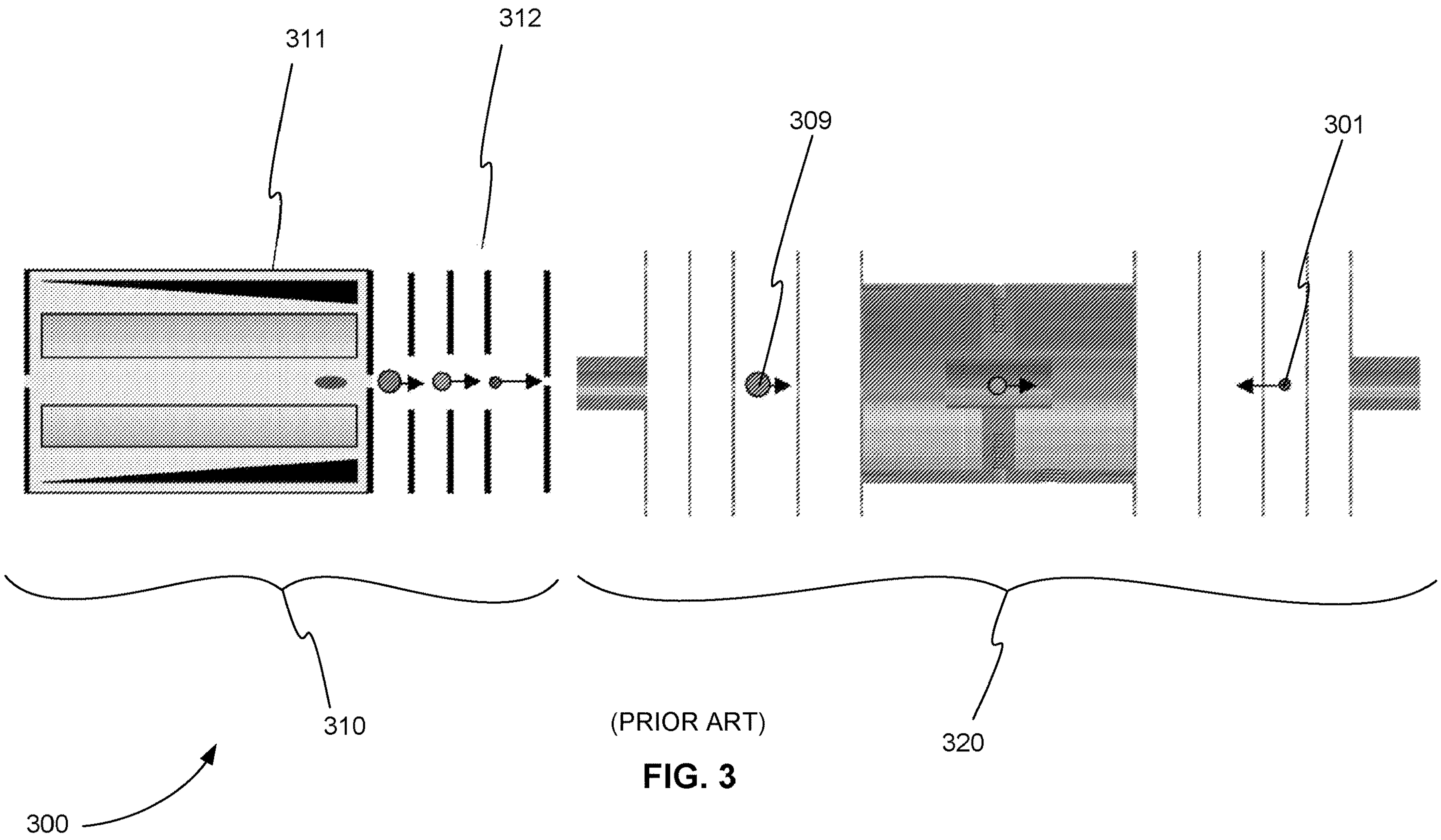
FIG. 1



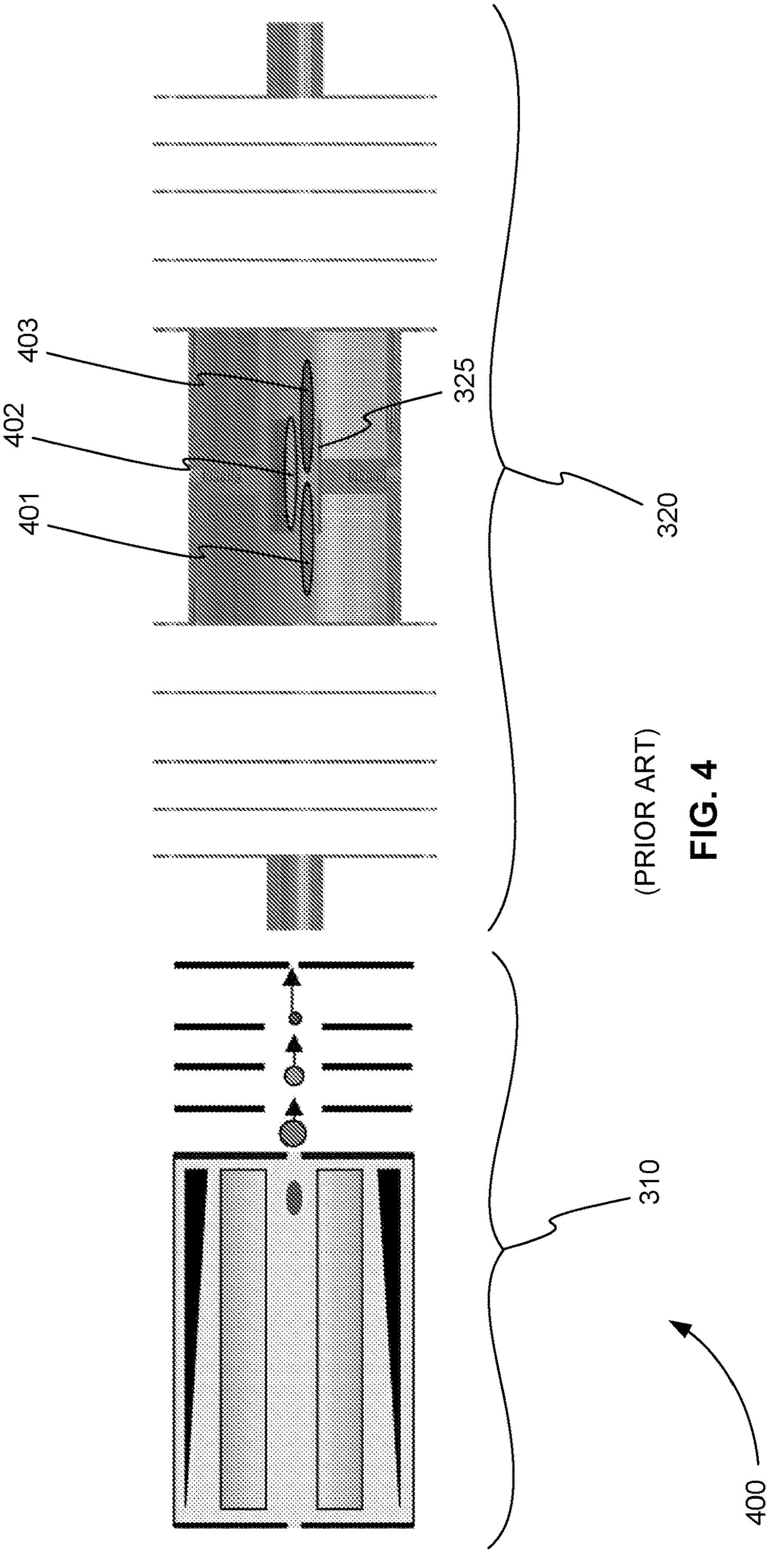
(PRIOR ART)

FIG. 2



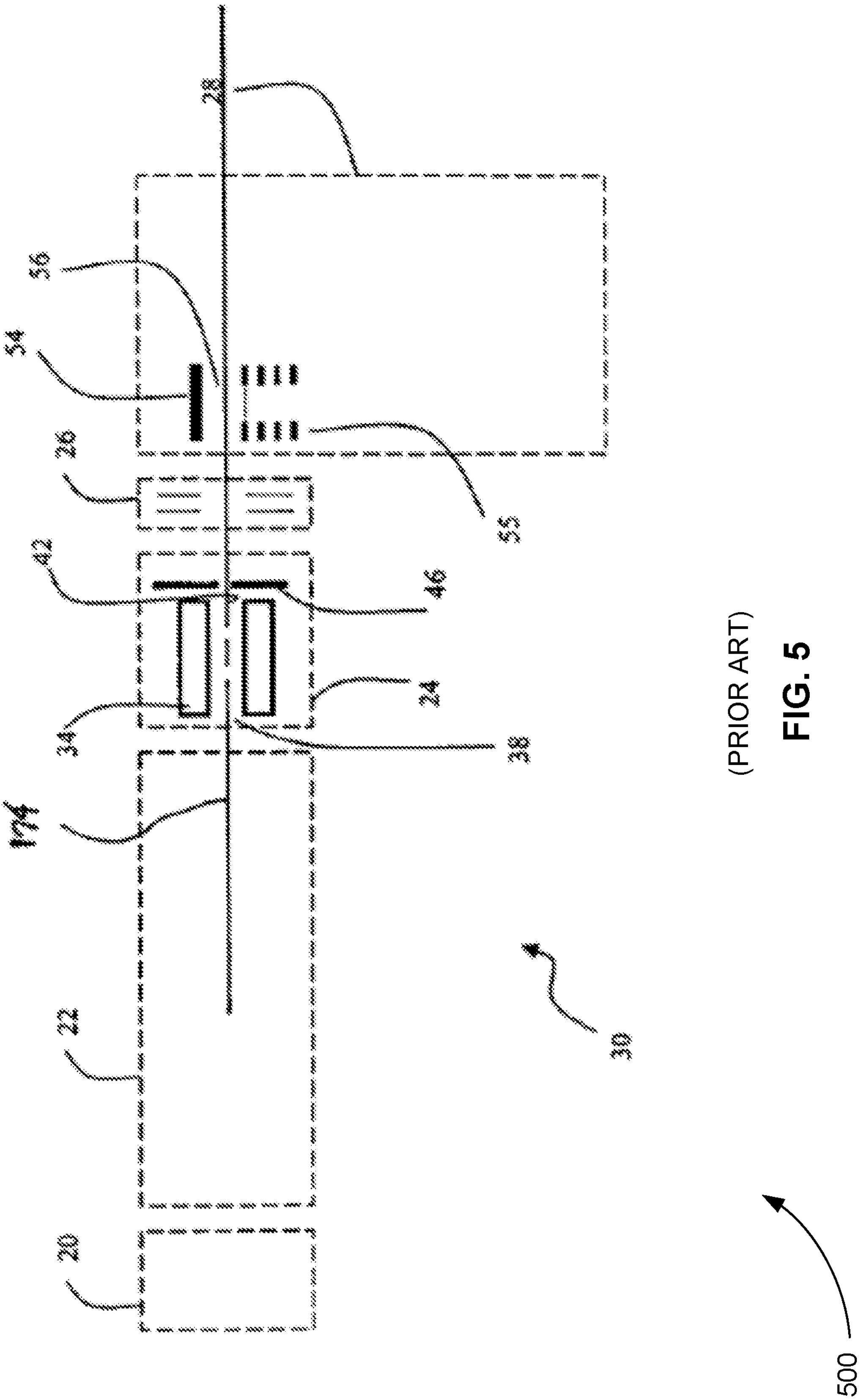
(PRIOR ART)

FIG. 3



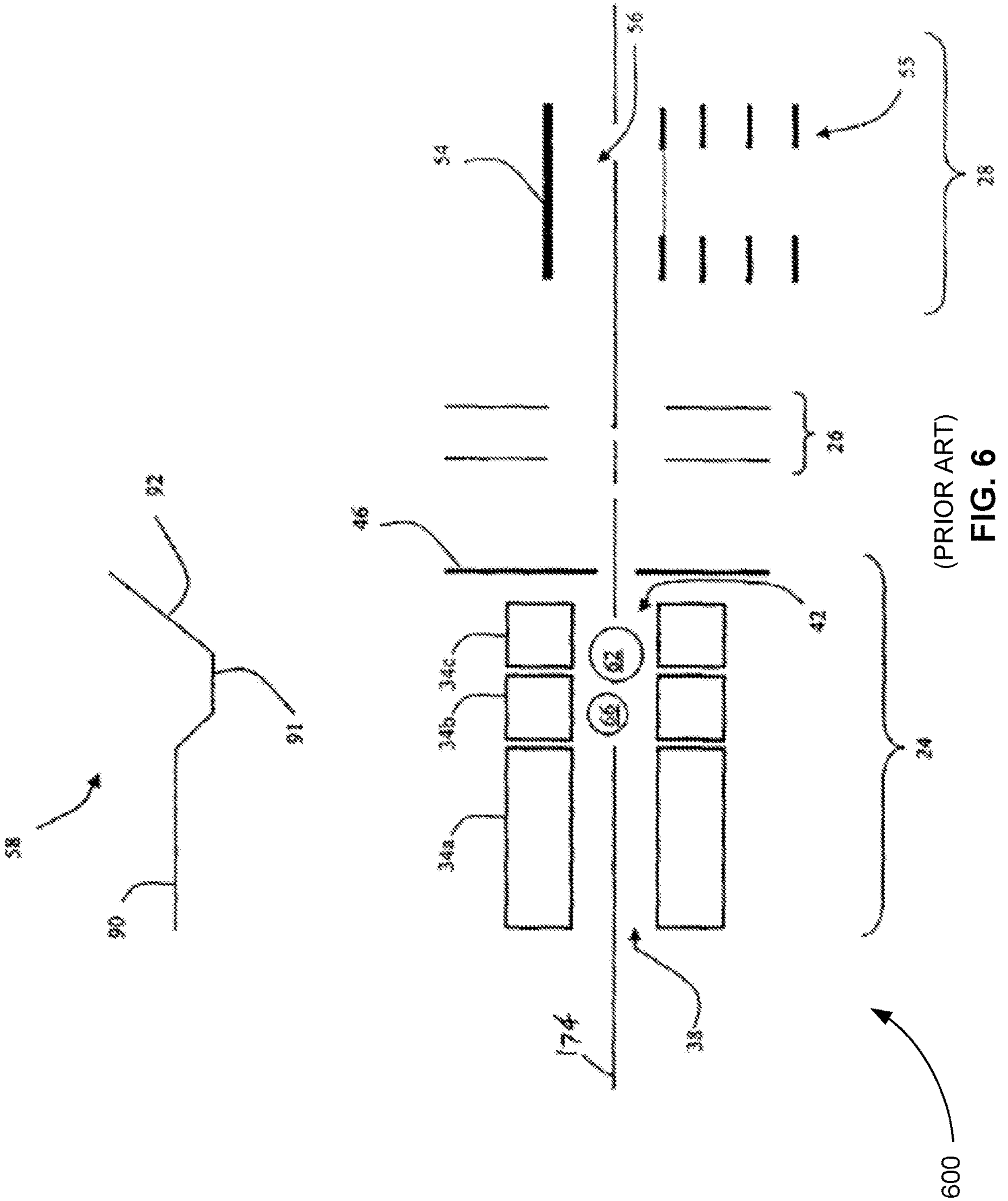
(PRIOR ART)

FIG. 4



(PRIOR ART)

FIG. 5



(PRIOR ART)

FIG. 6

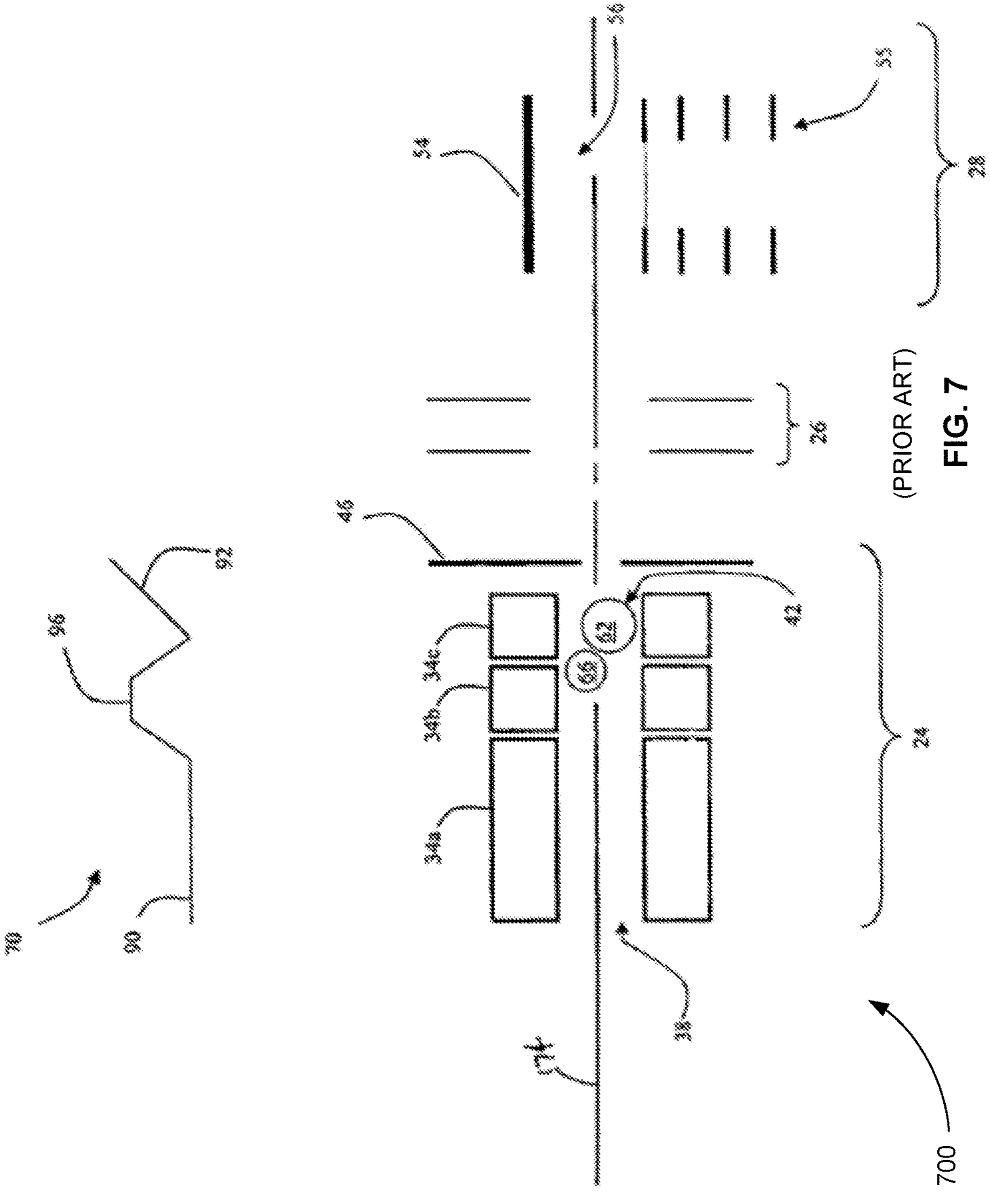


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FIG. 7

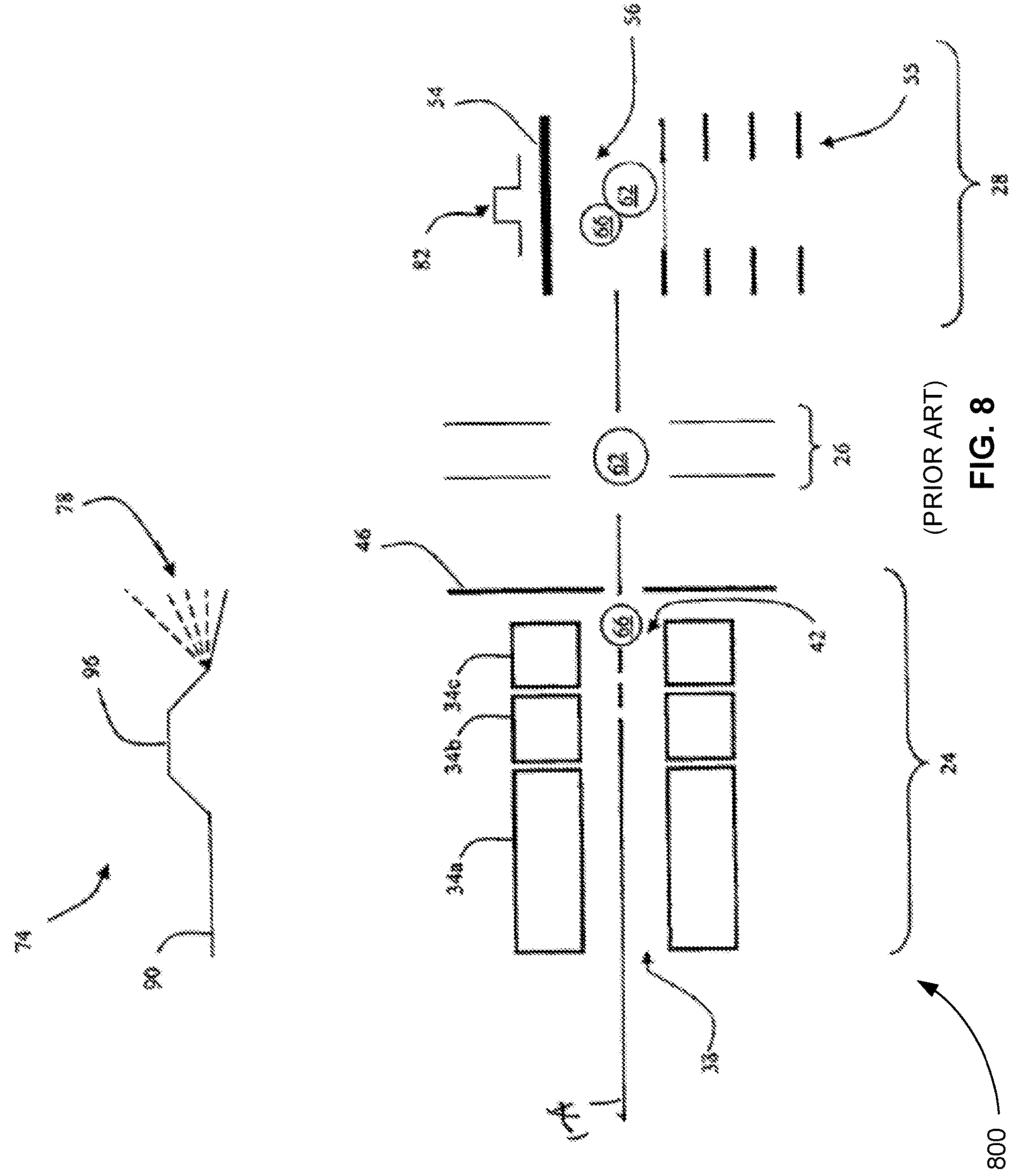

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FIG. 8

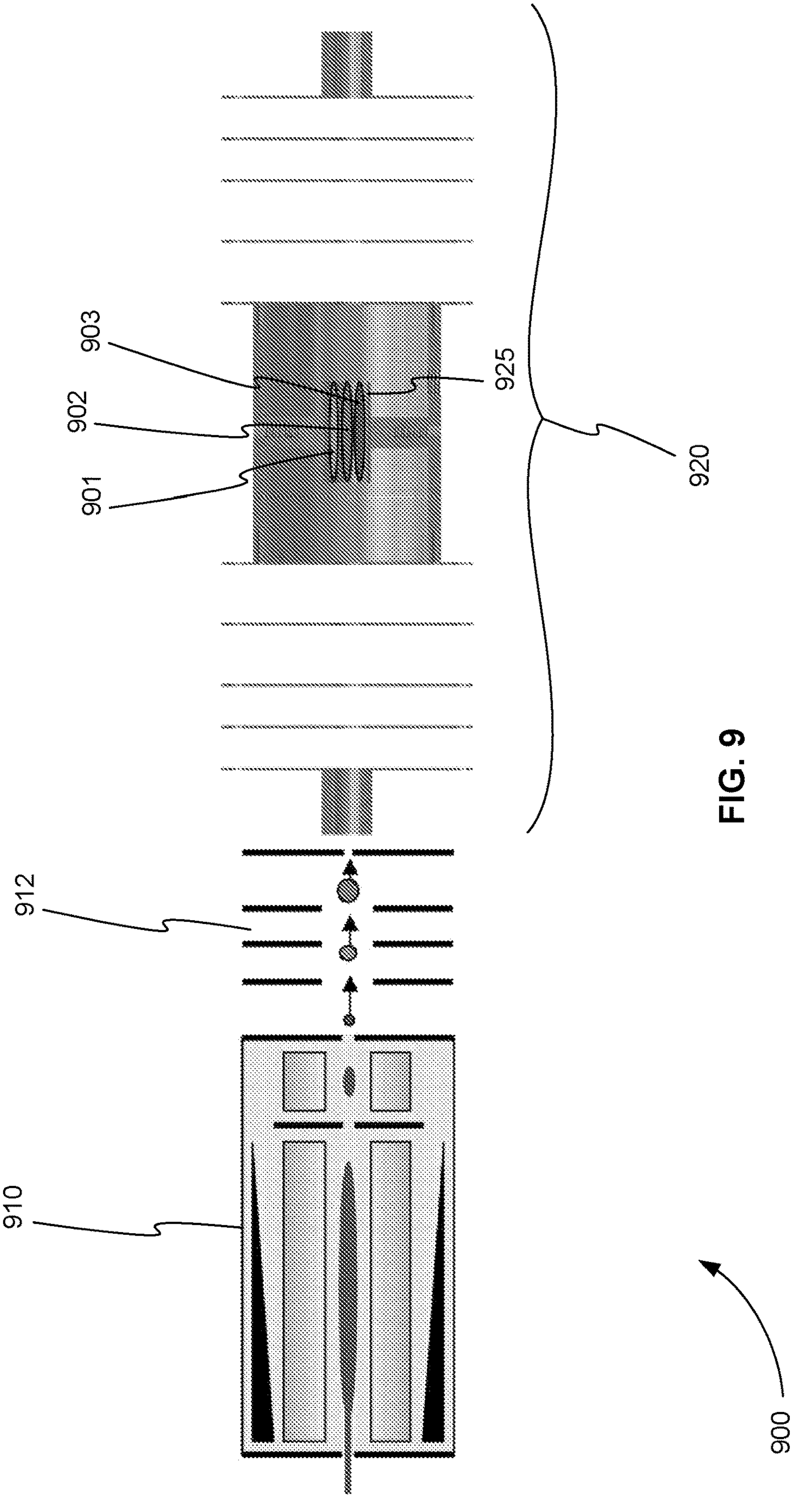

FIG. 9

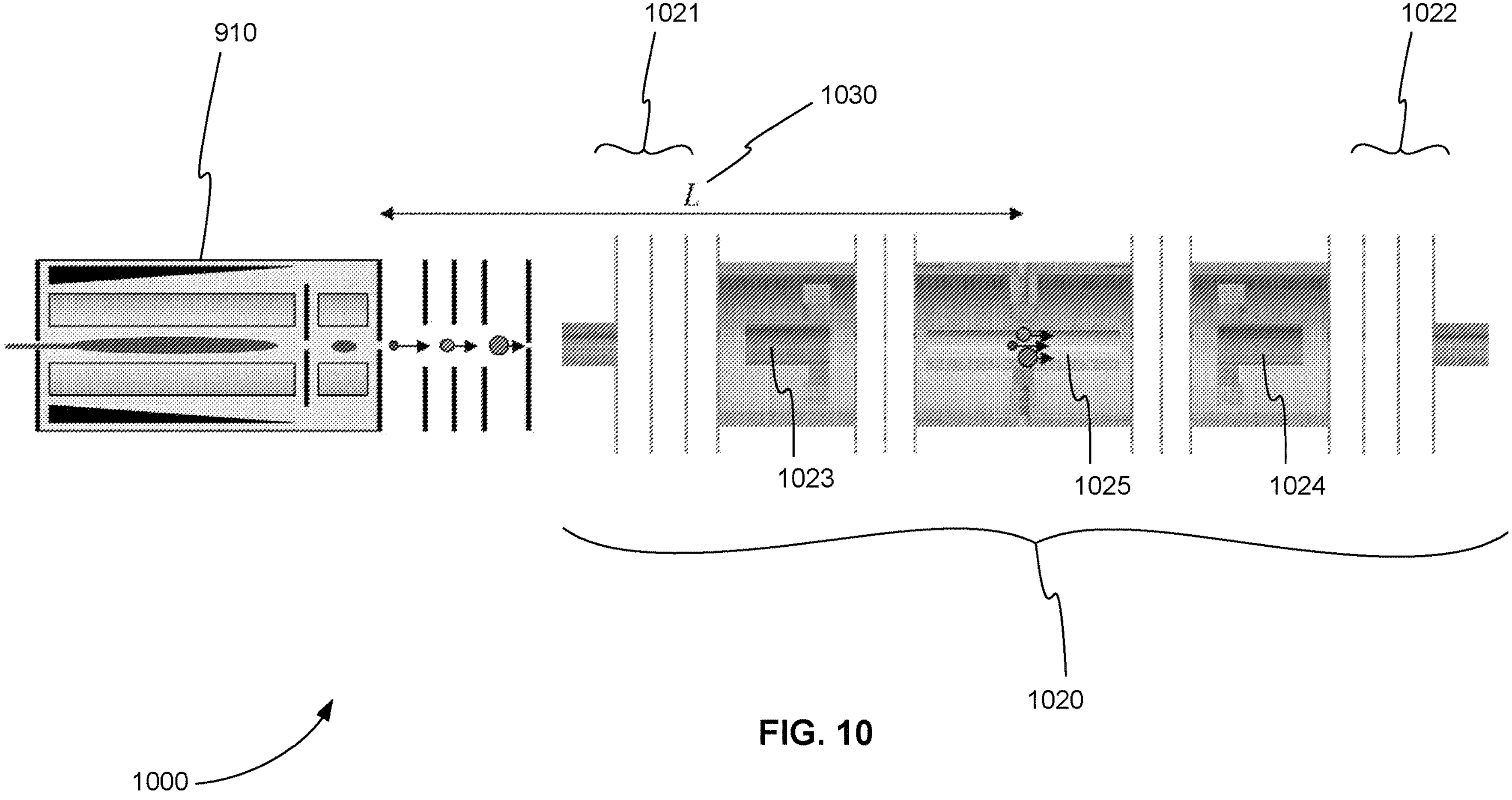

FIG. 10

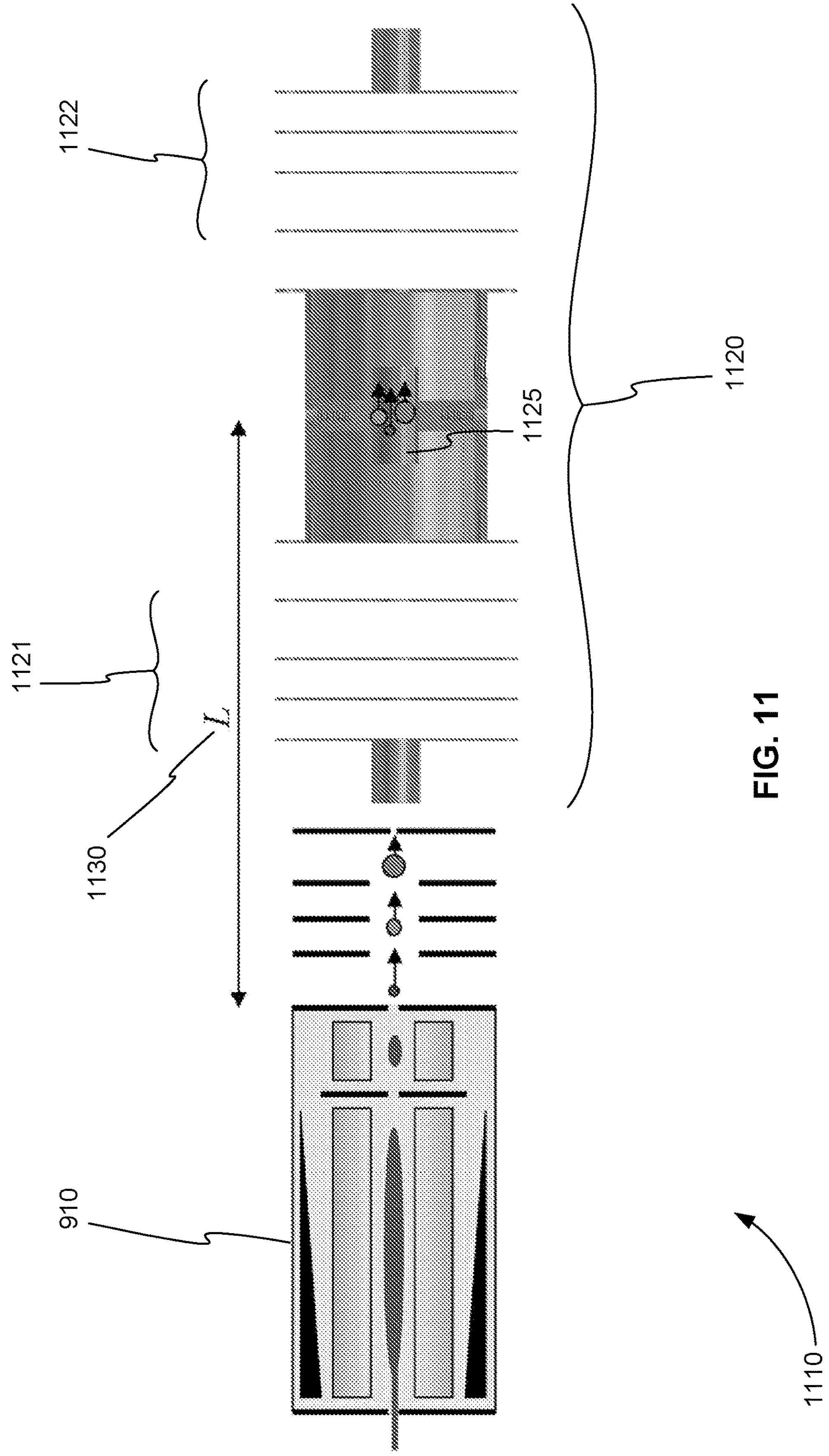

FIG. 11

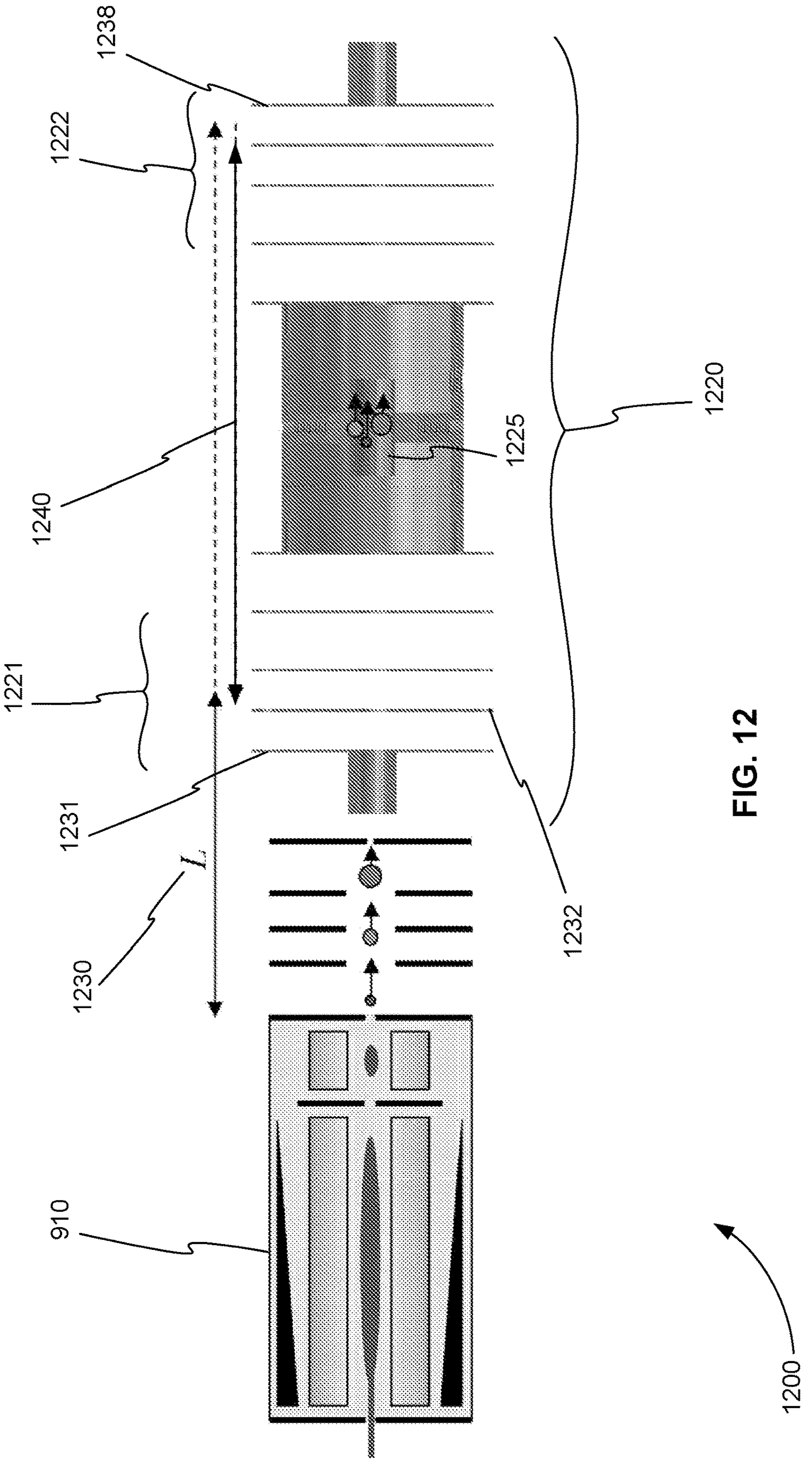

FIG. 12

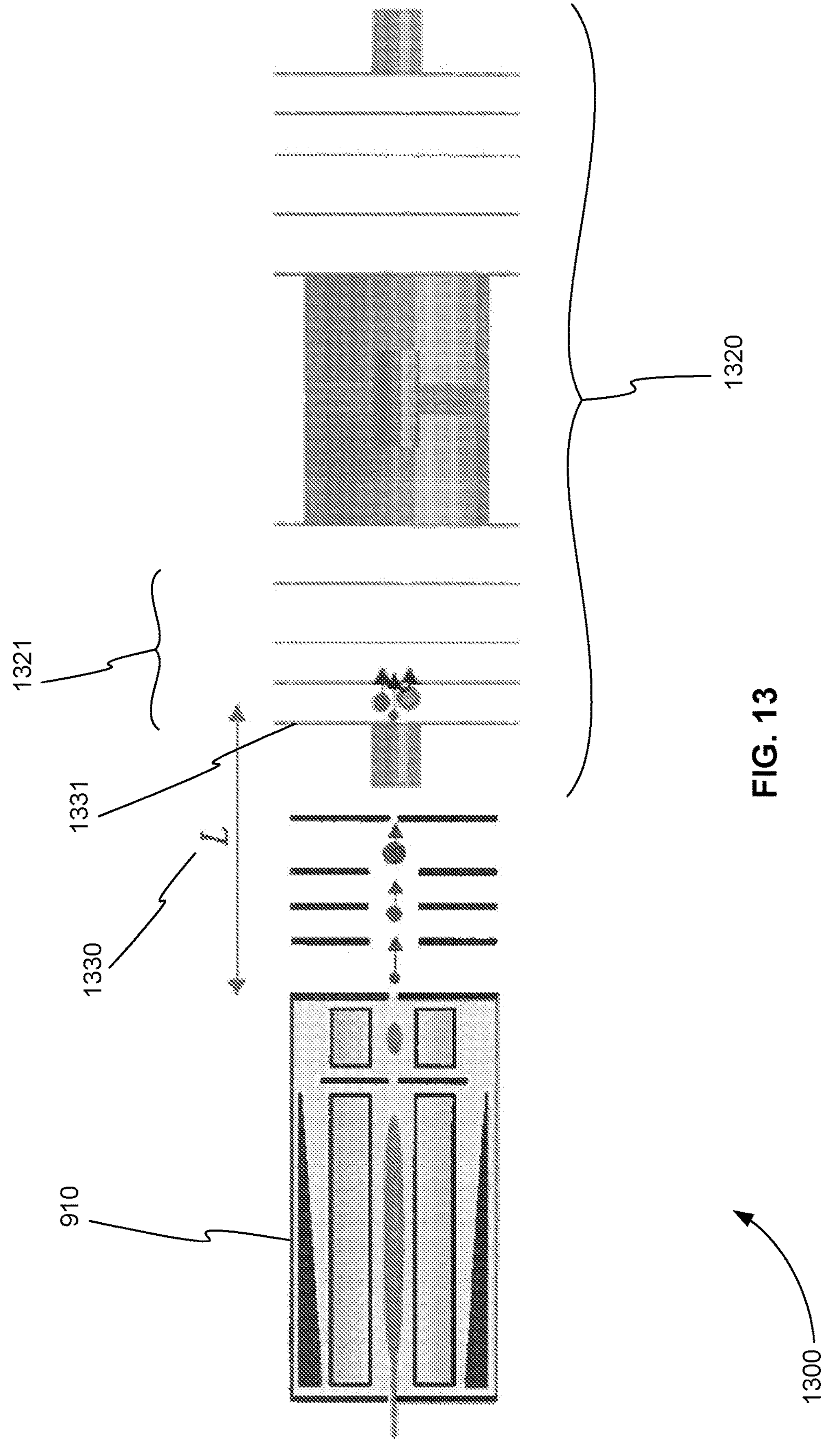

FIG. 13

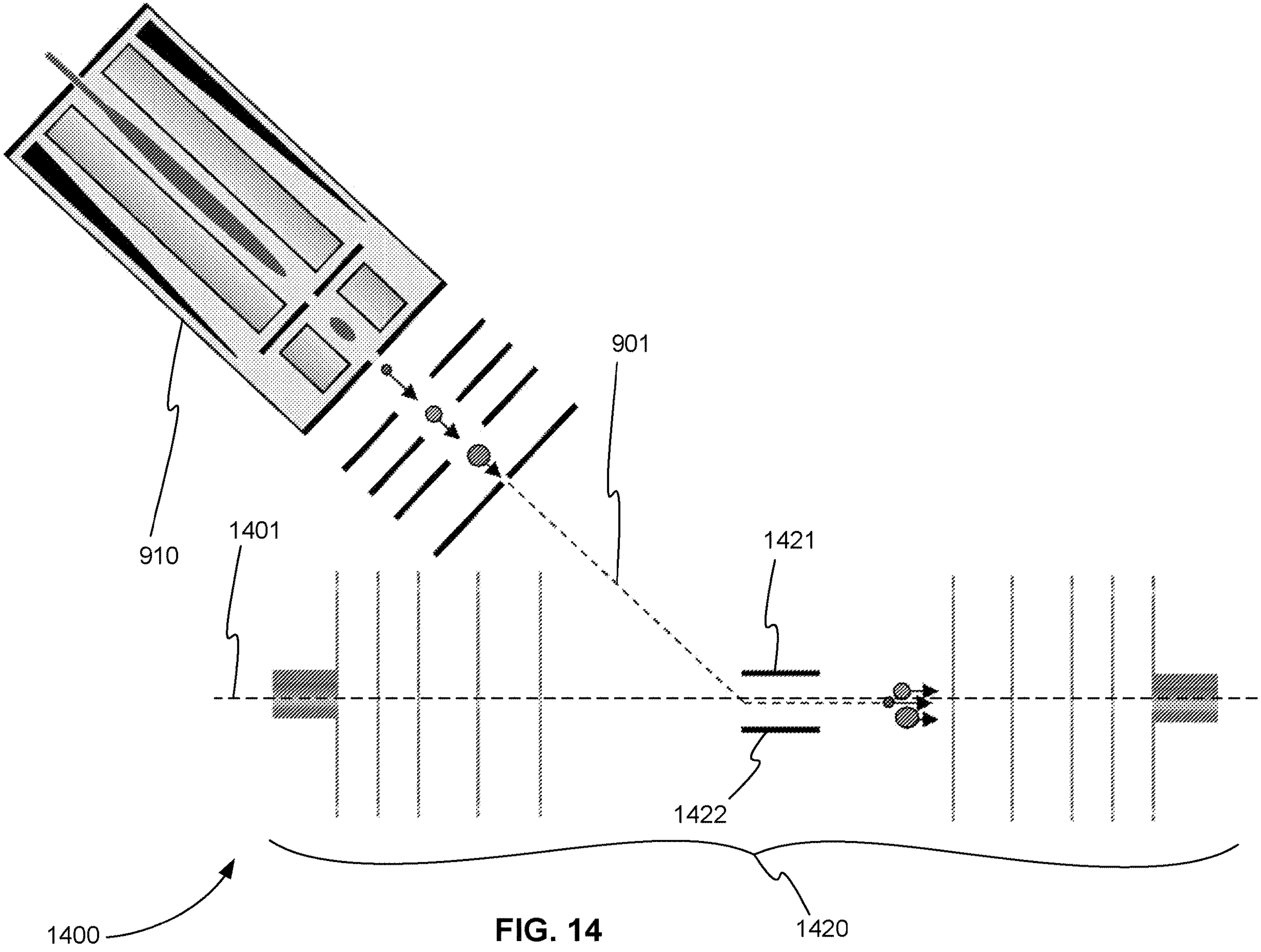

FIG. 14

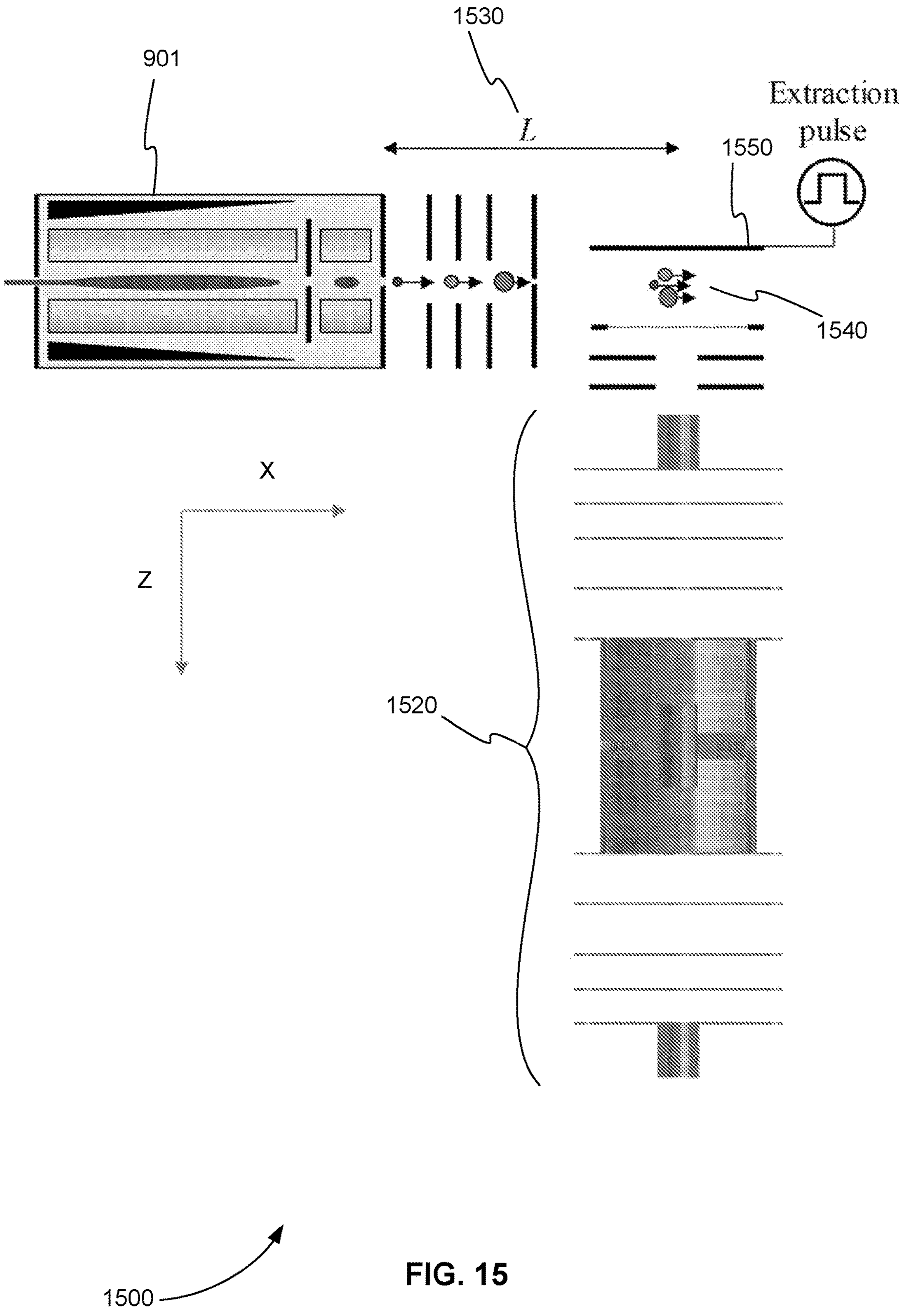

FIG. 15

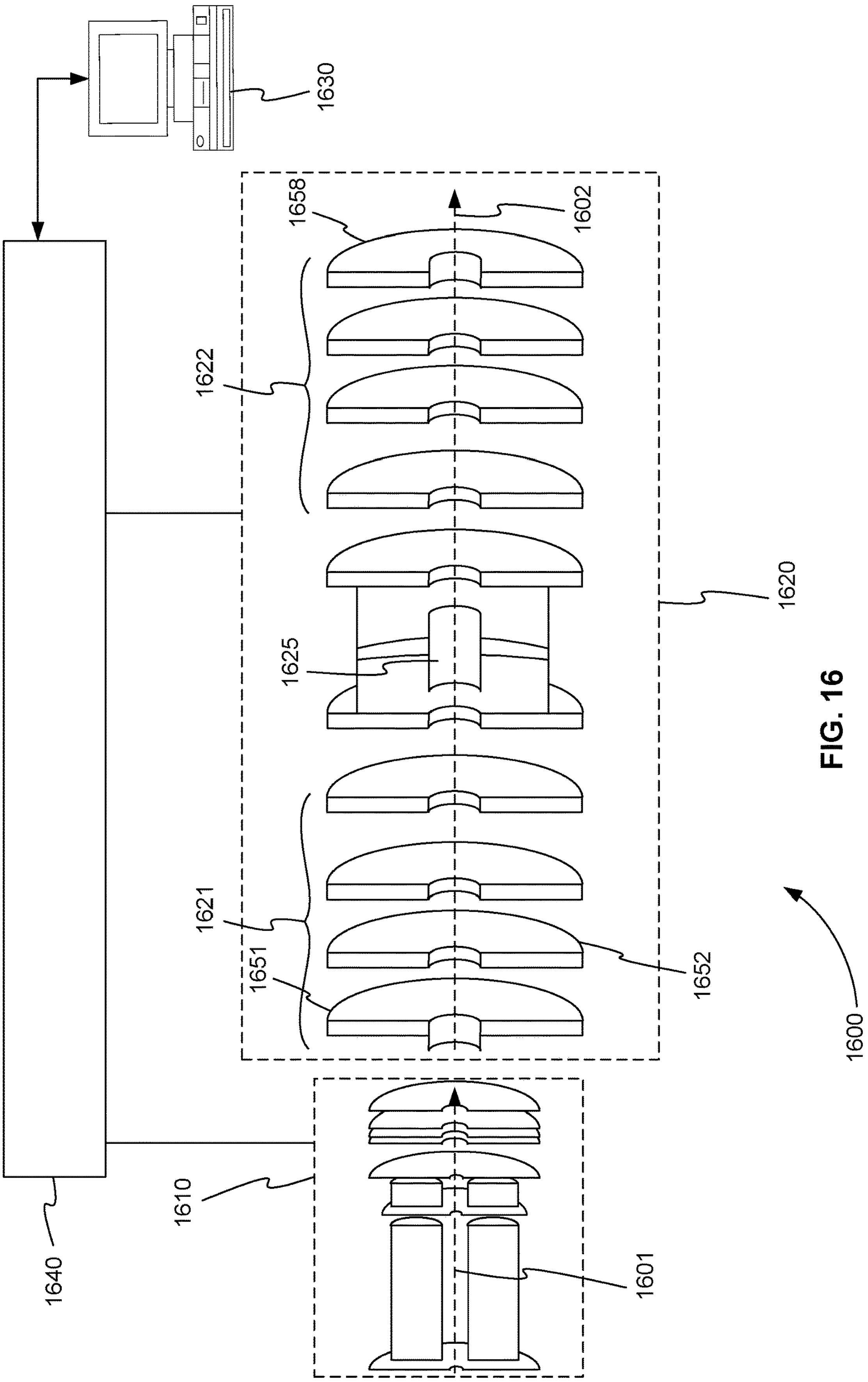
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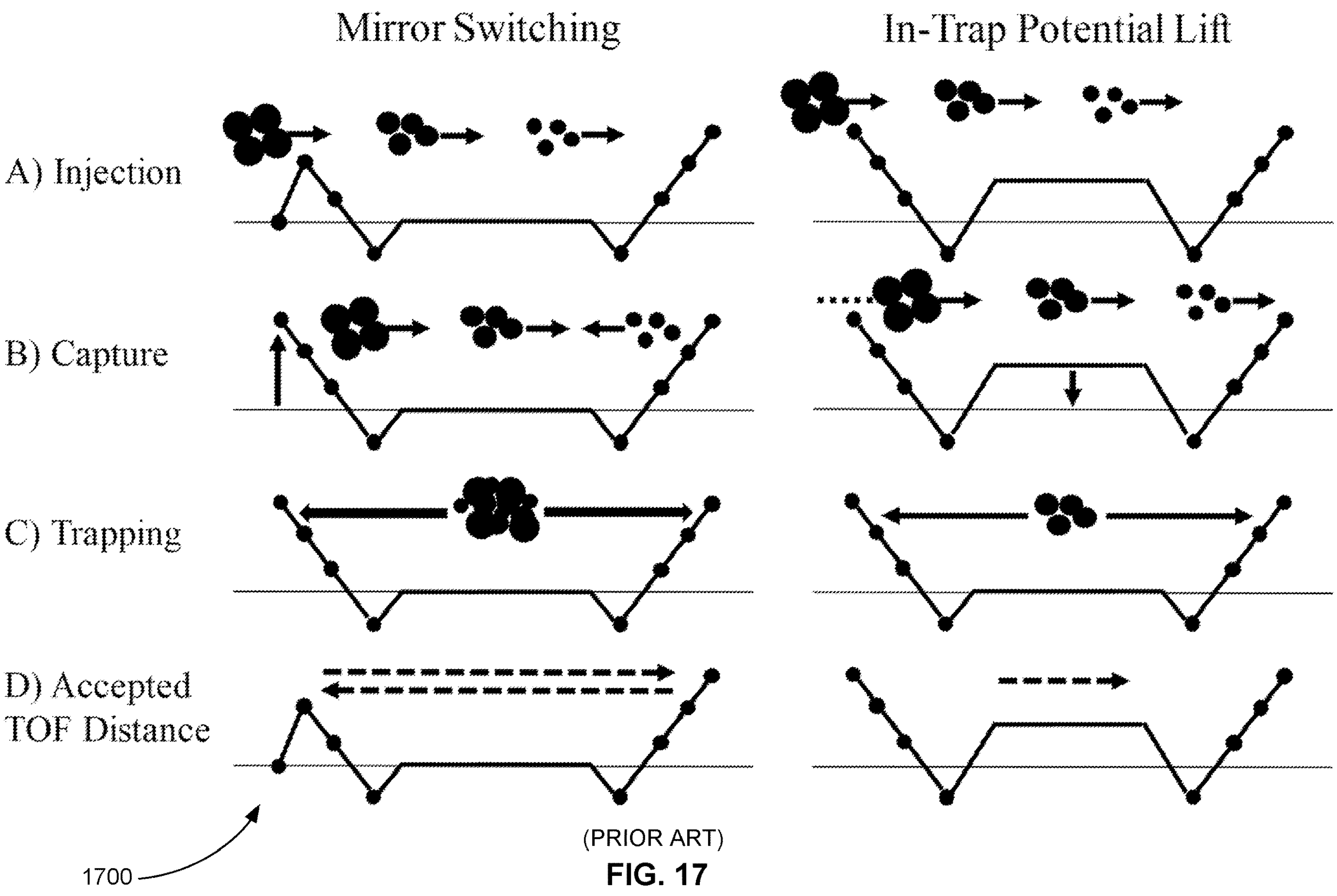
FIG. 16



(PRIOR ART)
FIG. 17

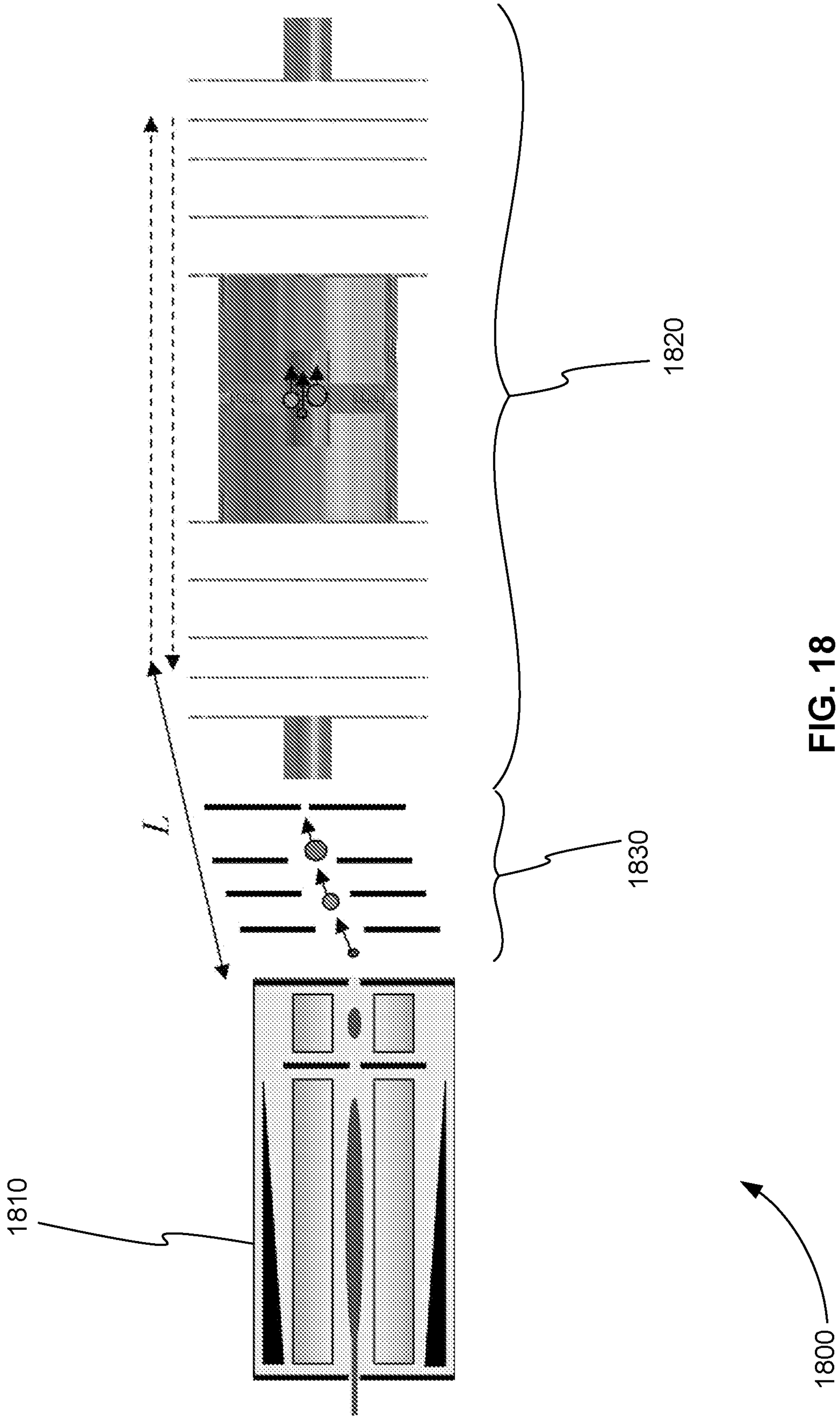


FIG. 18

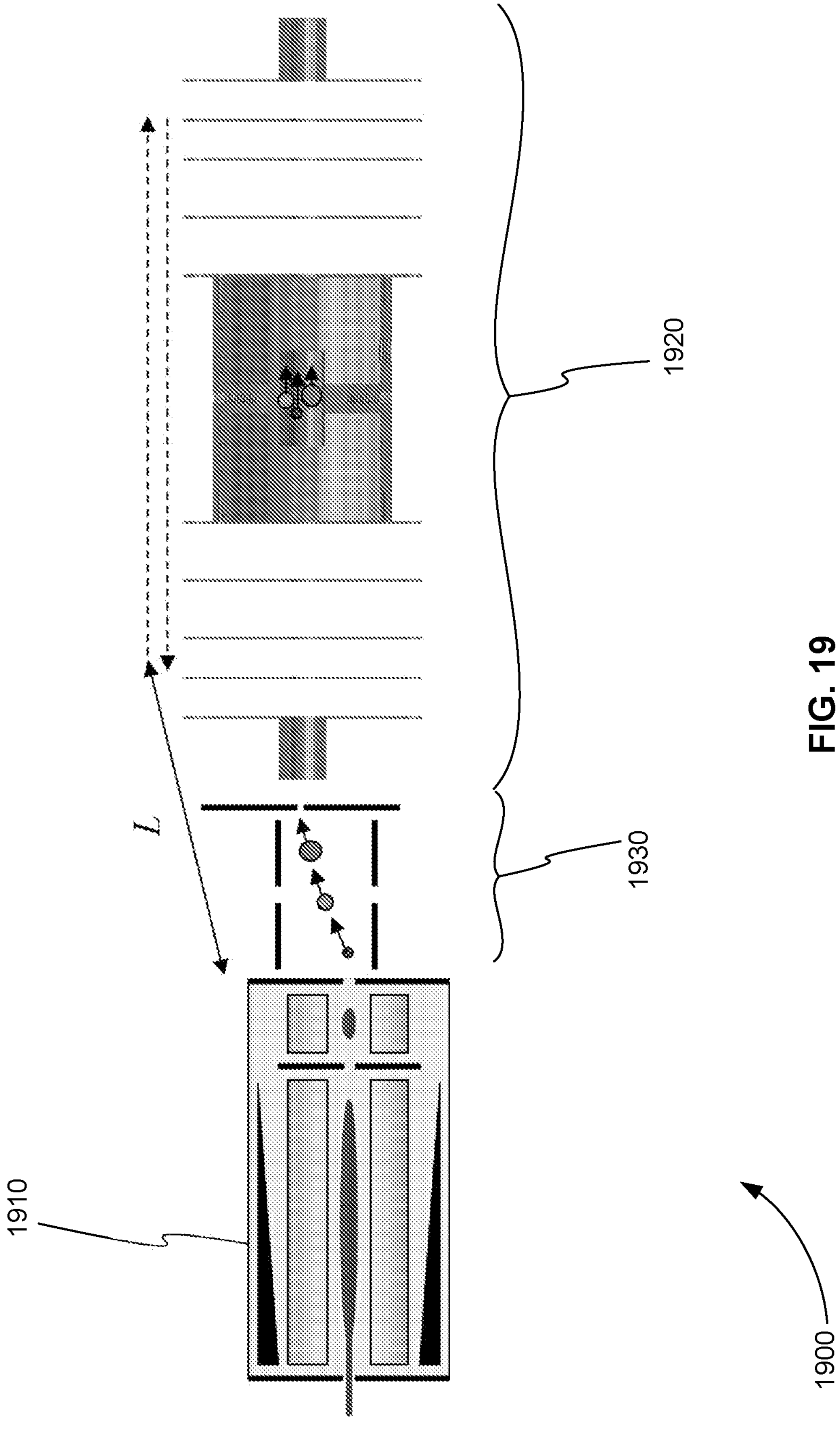


FIG. 19

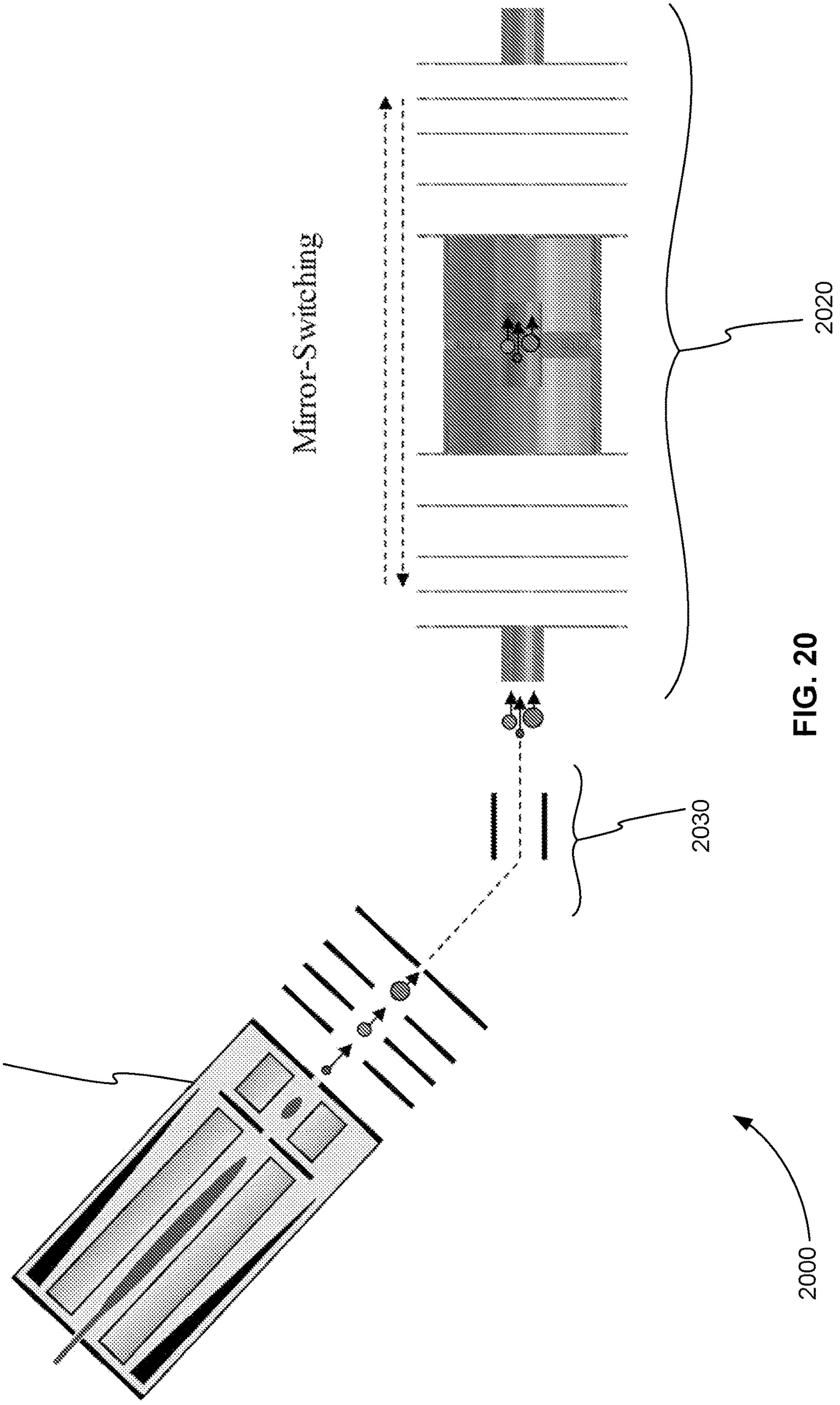


FIG. 20

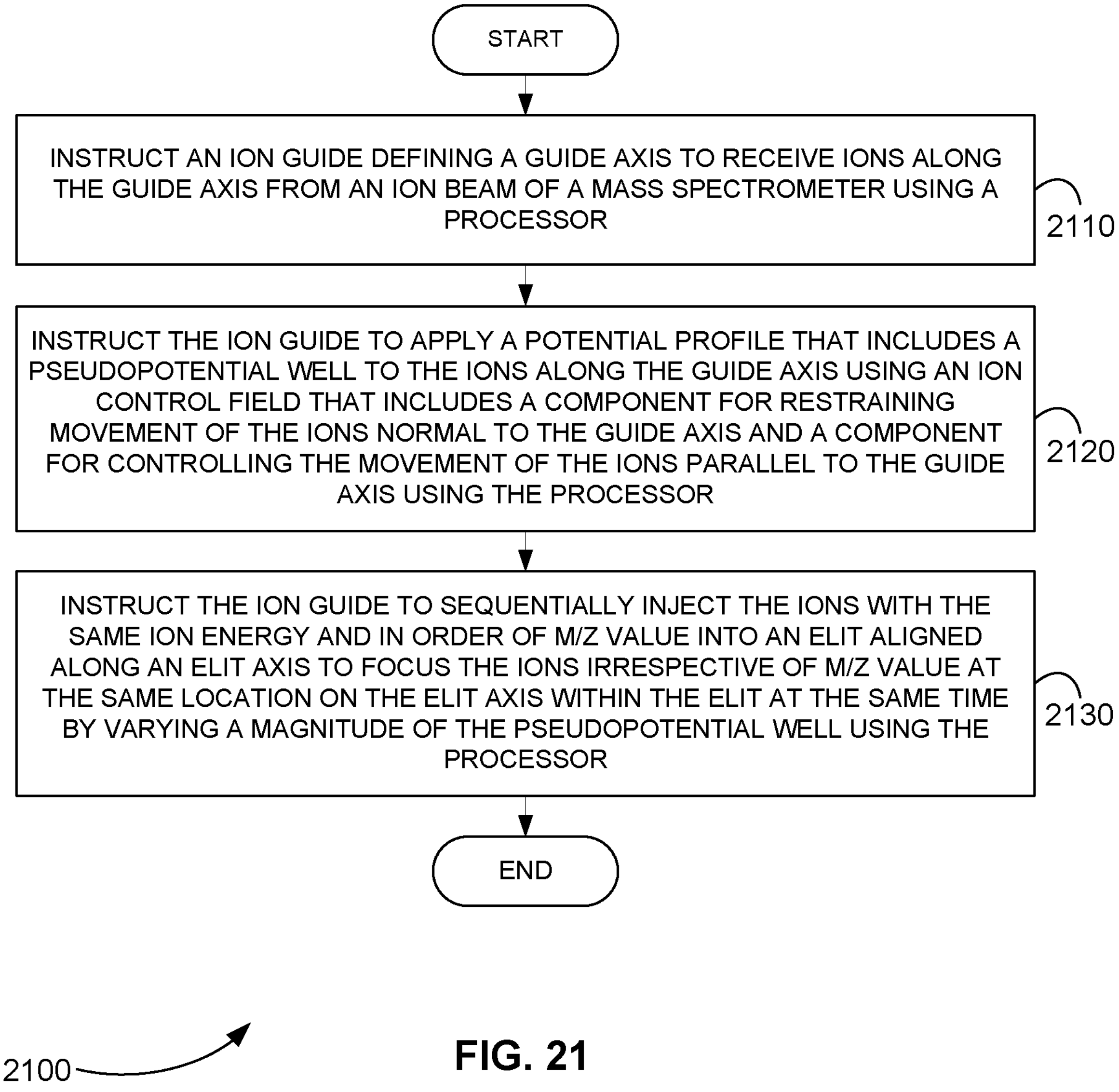

START
INSTRUCT AN ION GUIDE DEFINING A GUIDE AXIS TO RECEIVE IONS ALONG THE GUIDE AXIS FROM AN ION BEAM OF A MASS SPECTROMETER USING A PROCESSOR
2110
INSTRUCT THE ION GUIDE TO APPLY A POTENTIAL PROFILE THAT INCLUDES A PSEUDOPOTENTIAL WELL TO THE IONS ALONG THE GUIDE AXIS USING AN ION CONTROL FIELD THAT INCLUDES A COMPONENT FOR RESTRAINING MOVEMENT OF THE IONS NORMAL TO THE GUIDE AXIS AND A COMPONENT FOR CONTROLLING THE MOVEMENT OF THE IONS PARALLEL TO THE GUIDE AXIS USING THE PROCESSOR
2120
INSTRUCT THE ION GUIDE TO SEQUENTIALLY INJECT THE IONS WITH THE SAME ION ENERGY AND IN ORDER OF M/Z VALUE INTO AN ELIT ALIGNED ALONG AN ELIT AXIS TO FOCUS THE IONS IRRESPECTIVE OF M/Z VALUE AT THE SAME LOCATION ON THE ELIT AXIS WITHIN THE ELIT AT THE SAME TIME BY VARYING A MAGNITUDE OF THE PSEUDOPOTENTIAL WELL USING THE PROCESSOR
2130
END
2100

FIG. 21

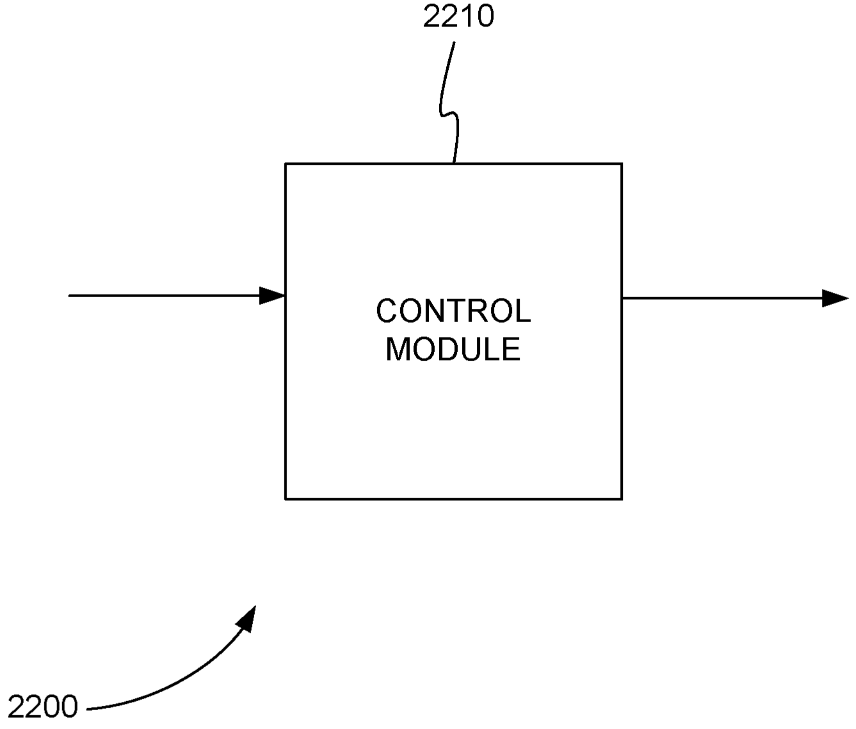


FIG. 22

ION INJECTION INTO AN ELECTROSTATIC LINEAR ION TRAP USING ZENO PULSING

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application Ser. No. 62/779,372, filed on Dec. 13, 2018, the content of which is incorporated by reference herein in its entirety.

INTRODUCTION

[0002] The teachings herein relate to a system for injecting ions into an electrostatic linear ion trap (ELIT) of a mass spectrometer so that ions with different mass-to-charge ratio (m/z) values are focused at the same location at the same time in the ELIT. More specifically, an ion guide positioned next to an ELIT sequentially injects the ions into the ELIT with the same ion energy and in order of decreasing m/z value to focus all ions irrespective of m/z value at the same location at the same time. This type of sequential injection of ions is referred to as Zeno pulsing.

[0003] The systems and methods disclosed herein can be performed in conjunction with a processor, controller, microcontroller, or computer system, such as the computer system of FIG. **1**.

[0004] ELIT-MS

[0005] An electrostatic linear ion trap mass spectrometer (ELIT-MS) is a type of mass spectrometer. An ELIT-MS includes an ELIT for performing mass analysis of ions. In an ELIT, electric current induced by oscillating ions in the trap is detected. The measured frequency of oscillation of the ions is used to calculate the m/z of the ions. For example, a Fourier transform is applied to the measured induced current.

[0006] Dziekonski et al., Int. J. Mass Spectrom. 410 (2016) p12-21, (the "Dziekonski Paper") describes an exemplary ELIT. The Dziekonski Paper is incorporated by reference herein.

[0007] FIG. **2** is a three-dimensional cutaway perspective view of an exemplary conventional ELIT **200**. ELIT **200** is similar to the ELIT of the Dziekonski Paper. ELIT **200** includes first set of electrode plates **210**, pickup electrode **215**, and second set of electrode plates **220**. First set of electrode plates **120** and second set of electrode plates **220** include holes in the center. Note that the end electrodes of first set of electrode plates **210** and second set of electrode plates **220** do not include holes in the center. However, this is only for simulation purposes. In an actual device, these end electrodes include holes in the center for the introduction and removal of ions from ELIT **200**.

[0008] In ELIT **200**, ions are introduced axially and are typically made to oscillate axially. The ions are made to oscillate axially by appropriately biasing first set of electrode plates **210** and second set of electrode plates **220** to reflect the ions. First set of electrode plates **210** and second set of electrode plates **220** are hereinafter referred to as reflectron plates because they are used to reflect ions.

[0009] When operated as a Fourier transform (FT) mass analyzer, pickup electrode **215** is used to measure the induced current, or image charge, produced by the oscillating ions. An FT is applied to the induced current signal measured from pickup electrode **215** to obtain the oscillation frequency. From the oscillation frequency or frequencies, the m/z of one or more ions is calculated.

[0010] ELIT Mass Range Limitation

[0011] FIG. **3** is an exemplary side view **300** of a system for performing conventional external ion injection into an ELIT. The system of FIG. **3** includes ion injection device **310** and ELIT **320**. Injection device **310** includes, for example, a quadrupole **311** followed by a focusing lens **312**.

[0012] Using a conventional external pulsed ion injection technique, injection device **310** accelerates all ions simultaneously, regardless of m/z. Because all ions are imparted with the same kinetic energy, the lighter ions arrive in ELIT **320** before the heavier ions. For example, ion **301** arrives in ELIT **320** before heavier ion **309**.

[0013] This time-of-flight (TOF) separation of the injected ions ultimately limits the accepted m/z range of an ELIT. In other words, an increased TOF separation of the ions injected into an ELIT decreases the m/z range that can be measured by the ELIT. Also, TOF separation of injected ions dictates that the size of an ELIT is inversely related to its accepted TOF distance (related to m/z range), ion frequencies, and observed resolution/time, and directly related to the propensity for ion coalescence.

[0014] Once ions are trapped in ELIT **320**, all plate potentials of ELIT **320** are fixed for the duration of the particular analysis. This means that the trapped ion energy is set via the offset of injection device **310** relative to the offset of ELIT **320**. Depending on the way in which ELIT **320** is operated, the offsets may need to be floated to several kV prior to ion injection, which can take tens to hundreds of milliseconds to accomplish. The ramping of the offset potential, therefore, limits the duty cycle to tens of Hertz at maximum. Ions can also be injected by pulsing the trapping potentials of the injection device **310** directly to the injection potentials. This eliminates the need for ramped potentials, potentially increasing the maximum duty cycle, but requires very accurate and reproducible pulses.

[0015] FIG. **4** is an exemplary side view **400** of the system of FIG. **3** showing how conventional external ion injection into an ELIT can cause positional dependencies in the measured ion intensity. In FIG. **4**, three ion populations of similar m/z **401**, **402**, and **403** are injected from conventional injection device **310** into ELIT **320** and captured in ELIT **320** via in-trap potential-lift. The TOF separation causes only half of ion population **401** and ion population **403** to be within lift electrode **325** at the moment of capture. The intensity of all three ion populations **401**, **402**, and **403** cannot simultaneously be maximized. Even ion population **402**, which is located within lift electrode **325**, would have its kinetic energy distribution affected by in-trap potential-lift due to the non-uniform electric field (electrodes are not gridded). These effects do exist for mirror-switching as well, although the effects are less noticeable considering the larger initial m/z range; only those ions near the extremes of the m/z range would be affected.

[0016] As a result, additional systems and methods are needed to inject ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT to increase the m/z range of the ELIT and to prevent positional dependencies in the measured ion intensities.

SUMMARY

[0017] A system, method, and a computer program product are disclosed for sequentially injecting ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT.

[0018] The system includes an ion guide and an ELIT. The ELIT includes a pickup electrode, a first set of reflectron plates, and a second set of reflectron plates. Each plate of the first set of reflectron plates includes a hole in the center and is aligned along an ELIT axis. Each plate of the second set of reflectron plates similarly includes a hole in the center and is aligned with the pickup electrode along the ELIT axis.

[0019] The ion guide defines a guide axis. The ion guide receives ions along the guide axis from an ion beam of a mass spectrometer. The ion guide applies a potential profile that includes a pseudopotential well to the ions along the guide axis using an ion control field. The ion control field includes a component for restraining movement of the ions normal to the guide axis and a component for controlling the movement of the ions parallel to the guide axis. Finally, the ion guide sequentially injects the ions into the ELIT with the same ion energy and in order of m/z value to focus the ions irrespective of m/z value at the same location on the ELIT axis within the ELIT at the same time by varying the magnitude of the pseudopotential well.

[0020] These and other features of the applicant's teachings are set forth herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] The skilled artisan will understand that the drawings, described below, are for illustration purposes only. The drawings are not intended to limit the scope of the present teachings in any way.

[0022] FIG. **1** is a block diagram that illustrates a computer system, upon which embodiments of the present teachings may be implemented.

[0023] FIG. **2** is a three-dimensional cutaway perspective view of an exemplary conventional electrostatic linear ion trap (ELIT).

[0024] FIG. **3** is an exemplary side view of a system for performing conventional external ion injection into an ELIT.

[0025] FIG. **4** is an exemplary side view of the system of FIG. **3** showing how conventional external ion injection into an ELIT can cause positional dependencies in the measured ion intensity.

[0026] FIG. **5** is an exemplary schematic diagram of the mass spectrometer described in U.S. Pat. No. 7,456,388.

[0027] FIG. **6** is an exemplary schematic diagram of the ion guide, electrostatic lens, and mass analyzer of U.S. Pat. No. 7,456,388 along with an accumulation potential profile of the ion guide.

[0028] FIG. **7** is an exemplary schematic diagram of the ion guide, electrostatic lens, and mass analyzer of U.S. Pat. No. 7,456,388 along with a pre-ejection potential profile of the ion guide.

[0029] FIG. **8** is an exemplary schematic diagram of the ion guide, electrostatic lens, and mass analyzer of U.S. Pat. No. 7,456,388 along with an ejection potential profile of the ion guide.

[0030] FIG. **9** is an exemplary side view of an ion guide sequentially injecting ions in order of decreasing m/z into an ELIT showing how this type of ion injection additionally minimizes aberrations in ion intensity due to positional dependencies of the ion clouds at the moment of capture, in accordance with various embodiments.

[0031] FIG. **10** is an exemplary side view of an ion guide sequentially injecting ions in order of decreasing m/z into a dual detector ELIT with a separate lift electrode showing the location of ion focus when the dual detector ELIT is performing in-trap potential lift ion capture, in accordance with various embodiments.

[0032] FIG. **11** is an exemplary side view of an ion guide sequentially injecting ions in order of decreasing m/z into a single detector ELIT showing the location of ion focus when the ELIT is performing in-trap potential lift ion capture, in accordance with various embodiments.

[0033] FIG. **12** is an exemplary side view of an ion guide sequentially injecting ions in order of decreasing m/z into an ELIT showing the location of ion focus when the ELIT is performing mirror-switching ion capture, in accordance with various embodiments.

[0034] FIG. **13** is an exemplary side view of an ion guide sequentially injecting ions in order of decreasing m/z into a single detector ELIT showing the location of ion focus when mirror-switching of an ELIT reflectron plate is used to perform in-trap potential lift ion capture, in accordance with various embodiments.

[0035] FIG. **14** is an exemplary side view of an ion guide positioned radially with respect to an ELIT to sequentially inject ions in order of decreasing m/z radially into the ELIT, in accordance with various embodiments.

[0036] FIG. **15** is an exemplary side view of an ion guide positioned orthogonal to an ELIT to sequentially inject ions in order of decreasing m/z radially into an extraction region for orthogonal acceleration into an ELIT showing the location of ion focus, in accordance with various embodiments.

[0037] FIG. **16** is a schematic diagram of a system for sequentially injecting ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT, in accordance with various embodiments.

[0038] FIG. **17** is a series of diagrams showing the potentials applied across an ELIT during ion injection, capture, and trapping for mirror switching and in-trap potential-lift.

[0039] FIG. **18** is a schematic diagram showing that transfer lenses can be used to offset the ion beam between an ion guide and an ELIT, in accordance with various embodiments.

[0040] FIG. **19** is a schematic diagram showing that deflection electrodes can be used to offset the ion beam between an ion guide and an ELIT, in accordance with various embodiments.

[0041] FIG. **20** is a schematic diagram showing that deflection electrodes can also be used to deflect the ion beam radially between an ion guide and an ELIT, in accordance with various embodiments.

[0042] FIG. **21** is a flowchart showing a method for sequentially injecting ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT, in accordance with various embodiments.

[0043] FIG. **22** is a schematic diagram of a system that includes one or more distinct software modules that perform a method a method for sequentially injecting ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT, in accordance with various embodiments.

[0044] Before one or more embodiments of the present teachings are described in detail, one skilled in the art will appreciate that the present teachings are not limited in their application to the details of construction, the arrangements of components, and the arrangement of steps set forth in the following detailed description or illustrated in the drawings. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting.

DESCRIPTION OF VARIOUS EMBODIMENTS

[0045] Computer-Implemented System

[0046] FIG. **1** is a block diagram that illustrates a computer system **100**, upon which embodiments of the present teachings may be implemented. Computer system **100** includes a bus **102** or other communication mechanism for communicating information, and a processor **104** coupled with bus **102** for processing information. Computer system **100** also includes a memory **106**, which can be a random access memory (RAM) or other dynamic storage device, coupled to bus **102** for storing instructions to be executed by processor **104**. Memory **106** also may be used for storing temporary variables or other intermediate information during execution of instructions to be executed by processor **104**. Computer system **100** further includes a read only memory (ROM) **108** or other static storage device coupled to bus **102** for storing static information and instructions for processor **104**. A storage device **110**, such as a magnetic disk or optical disk, is provided and coupled to bus **102** for storing information and instructions.

[0047] Computer system **100** may be coupled via bus **102** to a display **112**, such as a cathode ray tube (CRT) or liquid crystal display (LCD), for displaying information to a computer user. An input device **114**, including alphanumeric and other keys, is coupled to bus **102** for communicating information and command selections to processor **104**. Another type of user input device is cursor control **116**, such as a mouse, a trackball or cursor direction keys for communicating direction information and command selections to processor **104** and for controlling cursor movement on display **112**. This input device typically has two degrees of freedom in two axes, a first axis (i.e., x) and a second axis (i.e., y), that allows the device to specify positions in a plane.

[0048] A computer system **100** can perform the present teachings. Consistent with certain implementations of the present teachings, results are provided by computer system **100** in response to processor **104** executing one or more sequences of one or more instructions contained in memory **106**. Such instructions may be read into memory **106** from another computer-readable medium, such as storage device **110**. Execution of the sequences of instructions contained in memory **106** causes processor **104** to perform the process described herein. Alternatively, hard-wired circuitry may be used in place of or in combination with software instructions to implement the present teachings. Thus, implementations of the present teachings are not limited to any specific combination of hardware circuitry and software.

[0049] In various embodiments, computer system **100** can be connected to one or more other computer systems, like computer system **100**, across a network to form a networked system. The network can include a private network or a public network such as the Internet. In the networked system, one or more computer systems can store and serve the data to other computer systems. The one or more computer systems that store and serve the data can be referred to as servers or the cloud, in a cloud computing scenario. The one or more computer systems can include one or more web servers, for example. The other computer systems that send and receive data to and from the servers or the cloud can be referred to as client or cloud devices, for example.

[0050] The term "computer-readable medium" as used herein refers to any media that participates in providing instructions to processor **104** for execution. Such a medium may take many forms, including but not limited to, non-volatile media, volatile media, and transmission media. Non-volatile media includes, for example, optical or magnetic disks, such as storage device **110**. Volatile media includes dynamic memory, such as memory **106**. Transmission media includes coaxial cables, copper wire, and fiber optics, including the wires that comprise bus **102**.

[0051] Common forms of computer-readable media or computer program products include, for example, a floppy disk, a flexible disk, hard disk, magnetic tape, or any other magnetic medium, a CD-ROM, digital video disc (DVD), a Blu-ray Disc, any other optical medium, a thumb drive, a memory card, a RAM, PROM, and EPROM, a FLASH-EPROM, any other memory chip or cartridge, or any other tangible medium from which a computer can read.

[0052] Various forms of computer readable media may be involved in carrying one or more sequences of one or more instructions to processor **104** for execution. For example, the instructions may initially be carried on the magnetic disk of a remote computer. The remote computer can load the instructions into its dynamic memory and send the instructions over a telephone line using a modem. A modem local to computer system **100** can receive the data on the telephone line and use an infra-red transmitter to convert the data to an infra-red signal. An infra-red detector coupled to bus **102** can receive the data carried in the infra-red signal and place the data on bus **102**. Bus **102** carries the data to memory **106**, from which processor **104** retrieves and executes the instructions. The instructions received by memory **106** may optionally be stored on storage device **110** either before or after execution by processor **104**.

[0053] In accordance with various embodiments, instructions configured to be executed by a processor to perform a method are stored on a computer-readable medium. The computer-readable medium can be a device that stores digital information. For example, a computer-readable medium includes a compact disc read-only memory (CD-ROM) as is known in the art for storing software. The computer-readable medium is accessed by a processor suitable for executing instructions configured to be executed.

[0054] The following descriptions of various implementations of the present teachings have been presented for purposes of illustration and description. It is not exhaustive and does not limit the present teachings to the precise form disclosed. Modifications and variations are possible in light of the above teachings or may be acquired from practicing of the present teachings. Additionally, the described implementation includes software but the present teachings may be implemented as a combination of hardware and software or in hardware alone. The present teachings may be implemented with both object-oriented and non-object-oriented programming systems.

[0055] Zeno Pulsed Ion Injection into an ELIT

[0056] As described above, conventional external pulsed ion injection into an ELIT accelerates all ions simultaneously, regardless of m/z. This causes TOF separation of the injected ions and ultimately limits the accepted m/z range of an ELIT. This TOF separation can also cause positional dependencies in the ion intensities measured by an ELIT.

[0057] As a result, additional systems and methods are needed to inject ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT to increase the m/z range of the ELIT and to prevent positional dependencies in the measured ion intensities.

[0058] In various embodiments, Zeno pulsing is used to inject ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT to increase the m/z range of the ELIT and to prevent positional dependencies in the measured ion intensities.

[0059] U.S. Pat. No. 7,456,388 (hereinafter the "'388 Patent") issued on Nov. 25, 2008, and incorporated herein by reference, describes an ion guide that applies Zeno pulsing to orthogonally inject and focus ions with different m/z values at the same location at the same time in a TOF mass analyzer. The '388 Patent provides apparatus and methods that allow, for example, analysis of ions over broad m/z ranges with virtually no transmission losses. The ejection of ions from the ion guide is affected by creating conditions where all ions (regardless of m/z) may be made to arrive at a designated point in space, such as an extraction region or accelerator of a TOF mass analyzer, in a desired sequence or at a desired time and with roughly the same energy. Ions bunched in such a way can then be manipulated as a group, as, for example, by being extracted using a TOF extraction pulse and propelled along a desired path in order to arrive at the same spot on a TOF detector.

[0060] To make heavier and lighter ions with the same energy meet at a point in space such as the extraction region of a mass analyzer at substantially the same time, heavier ions can be ejected from the ion guide before lighter ions. Heavier ions of a given charge travel more slowly in an electromagnetic field than lighter ions of the same charge, and therefore can be made to arrive at the extraction region or other point at the same time as, or at a selected interval with respect to, the lighter ions if released within a field in a desired sequence. The '388 Patent provides mass-correlated ejection of ions from the ion guide in a desired sequence.

[0061] FIG. **5** is an exemplary schematic diagram **500** of the mass spectrometer described in the '388 Patent. Apparatus **30** comprises a mass spectrometer including ion source **20**, ion guide **24**, and TOF mass analyzer **28**. Ion source **20** can include any type of source compatible with the purposes described herein, including for example sources which provide ions through electrospray ionization (ESI), matrix-assisted laser desorption ionization (MALDI), ion bombardment, application of electrostatic fields (e.g., field ionization and field desorption), chemical ionization, etc.

[0062] Ions from ion source **20** may be passed into an ion manipulation region **22**, where ions can be subjected to ion beam focusing, ion selection, ion ejection, ion fragmentation, ion trapping, or any other generally known forms of ion analysis, ion chemistry reaction, ion trapping or ion transmission. Ions so manipulated can exit the manipulation region **22** and pass into an ion guide indicated by **24**.

[0063] Ion guide **24** defines axis **174** and comprises inlet **38**, exit **42** and exit aperture **46**. Ion guide **24** is adapted to generate or otherwise provide an ion control field comprising a component for restraining movement of ions in directions normal to the guide axis and a component for controlling the movement of ions parallel to the guide axis.

[0064] Ion guide **24** may include multiple sections or portions and/or auxiliary electrodes. As will be explained in greater detail below, ion guide **24** of spectrometer **30** is operable to eject ions of different masses and/or m/z ratios from exit **42**, while maintaining radial confinement along axis **174** within and beyond the ion guide **24**, such that the ions arrive at a desired point substantially along the axis of the ion guide, or in a desired proximity thereto, such as within extraction region **56** of TOF mass analyzer **28**, adjacent to push plate **54**, at substantially the same time, or in a desired sequence.

[0065] Ions ejected from ion guide **24** can be focused or otherwise processed by further apparatus, as, for example, electrostatic lens **26** (which may be considered a part of guide **24**) and/or mass analyzer **28**. Spectrometer **30** can also include devices such as push plate **54** and accelerating column **55**, which may, for example, be part of an extraction mechanism of mass analyzer **28**.

[0066] FIG. **6** is an exemplary schematic diagram **600** of the ion guide, electrostatic lens, and mass analyzer of the '388 Patent along with an accumulation potential profile of the ion guide. Accumulation potential profile **58** of FIG. **6** represents relative potential values, such as voltages or pressures, provided along axis **174** of ion guide **24**. The relative potential at portion **34***a* of ion guide **24** is indicated at **90**, the potential provided at portions **34***b* and **34***c* at **91**, and the potential gradient provided across portion **34***c* of the ion guide **24** and exit **42** of aperture **46** at **92**. Although not shown, an RF voltage is applied to ion guide **24** for providing confinement of the ions in the radial direction. Thus, an ion control field comprising a component for restraining movement of ions in directions normal to the guide axis and a component for controlling the movement of ions parallel to the guide axis is provided in ion guide **24**.

[0067] Provision of an accumulation potential **58** such as that shown in FIG. **6** within ion guide **24** allows large ions **62** (i.e., ions having large m/z values) and small ions **66** (i.e., ions having small m/z values) to traverse ion guide **24** in a direction parallel to axis **174** and settle into the preferential region proximate to electrodes **34***b* and **34***c* provided by the low potential at **91**, but prevents them from exiting the ion guide **24** by providing a higher potential on the aperture **46**. As will be familiar to those skilled in the relevant arts, it may be beneficial in some circumstances to apply a DC offset voltage on ion guide **24** in addition to the DC voltage mentioned above. In that instance, the overall potential profile **58** would be elevated by the corresponding DC offset voltage.

[0068] FIG. **7** is an exemplary schematic diagram **700** of the ion guide, electrostatic lens, and mass analyzer of the '388 Patent along with a pre-ejection potential profile of the ion guide. Pre-ejection potential profile **70** of FIG. **7** represents relative potential values, such as voltages or pressures, provided along axis **174** of ion guide **24**. In the example shown in FIG. **7**, pre-ejection profile **70** is similar to that described for accumulation potential profile **58** of FIG. **6**, but with potential **91** replaced by potential **96** at portion **34***b* of the ion guide **24** and corresponding changes in potential gradient **92**. Thus, a modified ion control field comprising a component for restraining movement of ions in directions normal to the guide axis and a component for controlling the movement of ions parallel to the guide axis is provided in ion guide **24**.

[0069] Provision of a pre-ejection profile **70** such as that shown in FIG. **7** can, for example, be used to cause ions **62** of relatively larger m/z and ions **66** of relatively smaller m/z to move within ion guide **24** in a direction parallel to axis **174** and settle within the region of ion guide **24** between portion **34***b* of the guide and aperture **46**. The potential at **96** can also prevent additional ions from entering ion guide **24** to a point beyond portion **34***b*.

[0070] FIG. **8** is an exemplary schematic diagram **800** of the ion guide, electrostatic lens, and mass analyzer of the '388 Patent along with an ejection potential profile of the ion guide. Ejection potential profile **74** of FIG. **8** can be created by, for example, applying an alternating current ("AC") voltage within portion **34***c* of ion guide **24** and/or at an exit aperture **46**, superimposed on voltages otherwise applied to the ion guide **24**. For example, appropriate RF and DC potentials may be applied to opposed pairs of electrodes within an ion guide **24**, along with suitable DC offset voltages applied to various sets of electrodes. The AC voltage can, for example, be superimposed over the RF voltage, while a difference between a potential at portion **34***c* and a potential at exit aperture **46** is reduced.

[0071] Ejection potential profile **74** along the axis of guide **24** can be provided by, for example, using a pseudopotential such as that represented by dashed lines at reference **78** in FIG. **8**.

[0072] For example, at the beginning of an ejection cycle such as cycle **74** represented in FIG. **8**, the magnitude or depth of a pseudopotential **78** may be chosen so that ions **62** of larger m/z ratios will leave exit **42** first. As the larger m/z ions **62** are released, the amplitude of the AC voltage may be gradually reduced to change the depth of the pseudopotential **78** well, and after a desired delay, to allow ions **66** of smaller m/z to leave ion guide **24**. The delay may be determined by controlling the rate of change of the AC amplitude, and may, for example, be chosen based on the masses and/or m/z ratios of ions **62** and **66** to achieve a desired delay. In the situation shown in FIG. **8**, ions **66** of smaller m/z travel faster than the ions **62** of larger m/z and gradient **78** is set accordingly. Gradient **78** is used to describe a variation of some parameter in space, but not in time.

[0073] Ions are provided to a desired point in space **56** disposed on, or substantially along, guide axis **174**, as for example an extraction region in a TOF analyzer for detection and mass analysis using methods generally known in the art. This is represented at the right-hand portion of FIG. **8**, where the different rates of travel of ions **62** and **66** have resulted in ions **62** and **66** reaching the orthogonal extraction region **56** in front of push plate **54**, at substantially the same time. At this point, an extraction pulse **82** may be applied to push plate **54** to pulse ions **62**, **66** through the accelerating column **55**.

[0074] As shown in FIGS. **5** through **8**, the '388 Patent describes performing Zeno pulsing in conjunction with TOF mass analyzer **28**. Zeno pulsing has also been used in conjunction with a Fourier-transform ion cyclotron resonance (FT-ICR) mass analyzer. Both of these instruments can use low-energy ion transfer conditions from the ion guide to the mass analyzer. In contrast, on an instrument using an ELIT, ions are transported through high electric fields, with kinetic energies on the order of thousands of electron-volts, making it not obvious that Zeno pulsing could be coupled to an ELIT device given the extremely long effective flight length.

[0075] In Zeno pulsing, the AC ramp time is chosen to bring the ions to a focus at an effective flight length, L. The slower the ramp down time, the longer the effective distance between the ion guide and focal point. However, the slower the AC ramp, the longer it takes ions to be released from the ion guide, thereby generating a longer the packet length at the focal point.

[0076] For orthogonal acceleration TOF mass spectrometers, an AC ramp (100-200 μs) will give an effective flight length of about 10 cm, with a packet width of around 5 cm, which is perfectly fine considering the size of the detector. For the signal induced on the image current/charge detector in an ELIT to be maximized, the ion packet must be shorter than the pickup electrode. For smaller ELITs, this would mean that the ion packet should be around 1 cm or less, with a mechanical focal length of 10-12 cm. As ion acceleration is performed on the way to the ELIT from the ion guide, high potentials are located in the intermediate transfer lenses. These high potentials increase the ion velocity, lowering the amount of time that the ions spread within the region, thereby greatly increasing the effective distance to the focal point (equivalent to a very large mechanical focal length).

[0077] For Zeno pulsing to be implemented on an ELIT, the effective focal distance and packet length must be reduced, both of which can be accomplished through a drastic reduction in the AC ramp down time (<10 us). Electrically, this comes with its own set of challenges as fast AC ramps require significantly more power and can compromise the linearity of the ramp. Still, depending on the magnitude of the intermediate potentials, it may not be possible to electronically reduce the effective focal distance enough, in which case only option is to move the ELIT further away from the ion guide. This negatively affects the mechanical tolerances of parts, alignment, cost, etc. In various embodiments, it is possible to bunch the ion packet closer to the exit lens in the ion guide using auxiliary electrodes, which decrease the downstream packet width without needing a faster AC ramp.

[0078] As described above, in Zeno pulsing, ions are released in order of high m/z to low m/z. This causes all ions, regardless of m/z, to come to a focus at a distance determined by the AC ramp time and electrode potentials. In various embodiments, when this focus is made to be within the lift electrode (in-trap potential-lift) or somewhere within the outermost electrodes of the ELIT (mirror-switching), the m/z range of the ELIT is maximized. In a preferred embodiment, the focus is made to coincide with the center of the ELIT.

[0079] When all ions of different m/z values come to a focus within the ELIT upon injection, the axial dimension of the ELIT becomes decoupled from the accepted TOF distance and m/z range. In various embodiments, therefore, the ELIT can be made shorter, thereby maximizing the ion frequencies, resolution/time, and minimizing coalescence effects. In addition, by moving the Einzel potential to the central element of the ELIT, and getting rid of two electrodes, the trap dimensions can be reduced even further. All things considered, the ion frequencies in a miniature ELIT could rival those found in the high-field Orbitrap.

[0080] FIG. **9** is an exemplary side view **900** of an ion guide sequentially injecting ions in order of decreasing m/z into an ELIT showing how this type of ion injection additionally minimizes aberrations in ion intensity due to positional dependencies of the ion clouds at the moment of capture, in accordance with various embodiments. In FIG. **9**, ion guide **910** sequentially injects ions in order of decreasing m/z into ELIT **920** and focuses the ions in the same location at the same time irrespective of m/z value using Zeno pulsing. Ions ejected from ion guide **910** can be focused or otherwise processed by further apparatus, as, for example, electrostatic lens **912** (which may be considered a part of guide **910**). Focusing the ions in the same location at the same time irrespective of m/z value using Zeno pulsing increases the m/z range of ELIT **920**.

[0081] It also, however, minimizes aberrations in ion intensity due to positional dependencies of the ion clouds at the moment of capture. For example, if three ion populations of similar m/z **901**, **902**, and **903** are injected from ion guide **910** into ELIT **920** via in-trap potential-lift, the Zeno pulsing causes all three ion populations **901**, **902**, and **903** to be within lift electrode **925** at the moment of capture. As all ion populations or clouds **901**, **902**, and **903** are overlapping in lift electrode **925**, all ion intensity measurements suffer equally, so there is no positional dependency in these measurements. The kinetic energy distribution of all ion populations **901**, **902**, and **903** would also be affected in the same way by the lift action, allowing the trapping potentials of ELIT **920** to be tuned to minimize the resulting TOF aberrations.

[0082] In various embodiments, using in-trap potential-lift, the trapped ion kinetic energy is decoupled from ion guide **910**. Therefore, ion guide **910** can be operated at about ground potential and ELIT **920** can be floated (negative for positive ion analysis, and vice versa). As no offsets need to be ramped, the duty cycle of the experiment can be increased such that it is ultimately limited by the rate at which ions cool and length of time the AC takes to ramp down (>1 kHz).

[0083] Unfortunately, if ion guide **910** is operated at about ground, lift electrode **925** needs to be pulsed to a high voltage to capture the ions. This requires a power supply with an extremely fast feedback loop and transient voltage recovery. Also, if lift electrode **925** coincides with the pickup detector, it is necessary to shield (protect, turn off) the preamplifier during the pulse. In various embodiments, it is possible to utilize two pulsed elements, one in the transfer lenses and one in ELIT **920**, to capture ions via in-trap potential-lift. Zeno pulsing would be used to focus all ions in the first pulsed electrode, wherein the potential would be pulsed higher than the trapping potentials of ELIT **920**. Ions can then enter ELIT **920** and be captured by pulsing the lift electrode to ground. This configuration allows ion guide **910** to be operated about ground and for lift electrode **925** to be pulsed to ground, minimizing voltage perturbations. Unfortunately, there will still be a TOF separation of the ions between the first pulsed electrode and ELIT **920**, thereby limiting the accepted m/z range.

[0084] FIG. **10** is an exemplary side view **1000** of an ion guide sequentially injecting ions in order of decreasing m/z into a dual detector ELIT with a separate lift electrode showing the location of ion focus when the dual detector ELIT is performing in-trap potential lift ion capture, in accordance with various embodiments. In FIG. **10**, ion guide **910** sequentially injects ions in order of decreasing m/z into dual detector ELIT **1020** and focuses the ions in the same location at the same time irrespective of m/z value using Zeno pulsing.

[0085] Dual detector ELIT **1020** is performing in-trap potential lift ion capture in FIG. **10**. In in-trap potential lift ion capture, ions are injected with more kinetic energy than the initial potential applied to any of the elements of dual detector ELIT **1020**. This means, for example, that, if no voltages are changed, ions coming from ion guide **910** would pass through dual detector ELIT **1020** once and exit the second set of reflectron plates **1022** and be detected by dual pickup detectors **1023** and **1024** for only one pass. In in-trap potential lift ion capture, however, once the ions reach central lift electrode **1025**, the potential applied to lift electrode **1025** is rapidly changed. This pulsed potential changes the total energy of the ions such that they are unable to overcome the potential barriers of first set of reflectron plates **1021** and second set of reflectron plates **1022**, so they remain trapped in dual detector ELIT **1020**.

[0086] As a result, in in-trap potential lift ion capture, ions need to be focused within lift electrode **1025**. FIG. **10** shows that ions with different m/z values are focused in dual detector ELIT **1020** at the same location at length **1030** from ion guide **910**. Ions are preferably focused at the center of lift electrode **1025** as shown in FIG. **10**. However, in various alternative embodiments, ions can be focused at any location in lift electrode **1025**. Note that in this case ion detection and ion capture are performed on separate electrodes, simplifying the required electronics.

[0087] FIG. **11** is an exemplary side view **1100** of an ion guide sequentially injecting ions in order of decreasing m/z into a single detector ELIT showing the location of ion focus when the ELIT is performing in-trap potential lift ion capture, in accordance with various embodiments. In FIG. **11**, ion guide **910** sequentially injects ions in order of decreasing m/z into single detector ELIT **1120** and focuses the ions in the same location at the same time irrespective of m/z value using Zeno pulsing.

[0088] Single detector ELIT **1120** is performing in-trap potential lift ion capture in FIG. **11**. Pickup electrode **1125** is used to detect the image current/charge resulting from ions passing through it and is also biased to act as lift electrode. In in-trap potential lift ion capture, once the ions reach central pickup electrode **1125**, a potential is applied to pickup electrode **1125**. This potential changes the total energy of the ions such that they are unable to overcome the potential barriers of first set of reflectron plates **1121** and second set of reflectron plates **1122**, so they remain trapped in single detector ELIT **1120**.

[0089] FIG. **11** shows that ions with different m/z values are focused in single detector ELIT **1120** at the same location at length **1130** from ion guide **910**. Ions are preferably focused at the center of pickup electrode **1125** as shown in FIG. **11**. However, in various alternative embodiments, ions can be focused at any location in pickup electrode **1125**.

[0090] FIG. **12** is an exemplary side view **1200** of an ion guide sequentially injecting ions in order of decreasing m/z into an ELIT showing the location of ion focus when the ELIT is performing mirror-switching ion capture, in accordance with various embodiments. In FIG. **12**, ion guide **910** sequentially injects ions in order of decreasing m/z into ELIT **1220** and focuses the ions in the same location at the same time irrespective of m/z value using Zeno pulsing.

[0091] ELIT **1120** is performing mirror-switching ion capture in FIG. **12**. In mirror-switching, a repulsive potential is applied to outermost reflectron plate **1231** of first set of reflectron plates **1221** and outermost reflectron plate **1238** of second set of reflectron plates **1222**. During ion capture, ions are trapped between outermost reflectron plate **1231** and outermost reflectron plate **1238**. In various embodiments, additional electrodes could be included in the first set of reflectron plates **1221** and the second set of reflectron plates **1222**. Also, in various embodiments, one or more electrode plates in the first set of reflectron plates **1221** and the second set of reflectron plates **1222** could have a repulsive potential applied to it.

[0092] During injection, a non-repulsive potential is applied to outermost reflectron plate **1231** allowing ions to enter into ELIT **1220**. Once the ions reach the focus location within ELIT **1220**, the repulsive potential is again applied to outermost reflectron plate **1231** to trap the ions within ELIT **1220**.

[0093] Using mirror-switching, the focus location of the Zeno pulse can be virtually anywhere within ELIT **1220**, so long as it is not in the vicinity of a switched potential, as this would alter the ion energy. In FIG. **12**, only the potential of outermost reflectron plate **1231** is switched. Thus, the focus location point can be anywhere in range **1240** between reflectron plates **1232** and **1238**. Ions, therefore, travel a minimum length **1230** from ion guide **910** to the focus location. Still, it is best practice for this focus location to be made at the center of ELIT **1220** in pickup electrode **1225**. Note that in the case of mirror-switching, the potential applied to detector **1225** is not pulsed to capture ions, greatly simplifying the detection electronics.

[0094] FIG. **13** is an exemplary side view **1300** of an ion guide sequentially injecting ions in order of decreasing m/z into a single detector ELIT showing the location of ion focus when mirror-switching of an ELIT reflectron plate is used to perform in-trap potential lift ion capture, in accordance with various embodiments. In FIG. **13**, ion guide **910** sequentially injects ions in order of decreasing m/z into ELIT **1320** and focuses the ions in the same location at the same time irrespective of m/z value using Zeno pulsing.

[0095] The capture action of mirror switching can be used to impart the trapped kinetic energy on all ions in an ELIT. In FIG. **13**, for example, mirror switching of reflectron plate **1331** of first set of reflectron plates **1321** has the effect of performing in-trap potential-lift on the ions. This requires that ion guide **910** and Zeno injection focus a very narrow ion packet to minimize the kinetic energy distribution and ion losses at a location near reflectron plate **1331** and at length **1330** from ion guide **910**. The in-trap potential-lift and trapping potentials of reflectron plate **1331** are likely unequal. Therefore, two different pulsed potentials would need to be applied to reflectron plate **1331**; one to lift the potential energy of the ions and accelerate them into the ELIT, as depicted in FIG. **13**, and one to increase the repulsive potential of the electrode once ions enter the ELIT and are not in the vicinity of the pulsed potential.

[0096] FIG. **14** is an exemplary side view **1400** of an ion guide positioned radially with respect to an ELIT to sequentially inject ions in order of decreasing m/z radially into the ELIT, in accordance with various embodiments. In FIG. **14**, ion guide **910** defines guide axis **901**, and ELIT **1420** defines ELIT axis **1401**. Ion guide **910** is positioned radially with respect to ELIT **1420** so that guide axis **901** intersects ELIT axis **1401** at an angle of less than ninety degrees at the location of ion focus on ELIT axis **1401**.

[0097] Ion guide **910** sequentially injects ions in order of decreasing m/z along guide axis **901** and into ELIT **1420**. Ion guide **910** focuses the ions at the intersection of guide axis **901** and ELIT axis **1401** at the same time irrespective of m/z value using Zeno pulsing.

[0098] In various embodiments, ions can be focused anywhere along ELIT axis **1401**. For the purposes of FIG. **14**, the pickup tube and detector of ELIT **1420** are not shown. Radial injection of ions into ELIT **1420** allows other mass spectrometry devices to be connected to the input or output of ELIT **1420**. Deflection electrodes **1421** and **1422** are used to change the ion trajectory from guide axis **901** to ELIT axis **1401** by applying dissimilar potentials to the two electrodes. A non-repulsive potential is applied to deflection electrode **1421** and a repulsive potential is applied to deflection electrode **1422**. Once ions pass through deflection electrodes **1421** and **1422**, the potential of deflection electrode **1421** and deflection electrode **1422** are made to be equal, thereby capturing ions in ELIT **1420**.

[0099] FIG. **15** is an exemplary side view **1500** of an ion guide positioned orthogonal to an ELIT to sequentially inject ions in order of decreasing m/z radially into an extraction region for orthogonal acceleration into an ELIT showing the location of ion focus, in accordance with various embodiments. As in the '388 Patent, ion guide **910** sequentially injects ions in order of decreasing m/z into extraction region **1540** and focuses the ions in the same location at the same time irrespective of m/z value using Zeno pulsing. The ions are focused at length **1530** from ion guide **910** in extraction region **1540**.

[0100] In this case, the m/z is still maximized. However, there is still TOF separation between the extraction region **1540** and ELIT **1520**, thereby making the dimensions of ELIT an important factor in determining the figures-of-merit for ELIT **1520**. Additional focusing elements are also required to shape the ion beam, considering that the position distribution of the ion cloud would be widest in the X dimension within the accelerator **1550**, while ELIT **1520** requires an ion packet that is oriented along the Z dimension.

[0101] System for Injecting Ions into an ELIT

[0102] FIG. **16** is a schematic diagram **1600** of a system for sequentially injecting ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT, in accordance with various embodiments. The system of FIG. **16** includes ion guide **1610** and ELIT **1620**.

[0103] ELIT **1620** includes pickup electrode **1625**, first set of reflectron plates **1621**, and second set of reflectron plates **1622**. Each plate of first set of reflectron plates **1621** includes a hole in the center and is aligned along ELIT axis **1602**. Each plate of second set of reflectron plates **1622** similarly includes a hole in the center and is aligned along ELIT axis **1602**.

[0104] Ion guide **1610** defines guide axis **1601**. Ion guide **1610** receives ions along guide axis **1601** from an ion beam of a mass spectrometer (not shown). Ion guide **1610** applies a potential profile that includes a pseudopotential well to the ions along guide axis **1601** using an ion control field. The ion control field includes a component for restraining movement of the ions normal to guide axis **1601** and a component for controlling the movement of the ions parallel to guide axis **1601**. Finally, ion guide **1610** sequentially injects the ions into ELIT **1620** with the same ion energy and in order of m/z value to focus the ions irrespective of m/z value at the same location on ELIT axis **1602** within ELIT **1620** at the same time by varying the magnitude of the pseudopotential well.

[0105] FIG. **17** is a series of diagrams **1700** showing the potentials applied across an ELIT during ion injection, capture, and trapping for mirror switching and in-trap potential-lift.

[0106] Returning to FIG. **16**, in various embodiments, ELIT **1620** traps the ions along ELIT axis **1602** using in-trap potential-lift after the sequential injection into ELIT **1620** from ion guide **1610**.

[0107] If ELIT **1620** is a single detector ELIT as shown in FIG. **16**, then pickup electrode **1625** is also a lift electrode. Because in-trap potential-lift ion capture is used, the same location on ELIT axis **1602** is a location within a portion of the ELIT axis surrounded by the lift electrode (pickup electrode **1625**). FIG. **16** is an example of a single detector ELIT, but is not the only configuration. It is possible to perform ion detection on the reflectron plate electrodes so that the tube is only used for in-trap potential-lift.

[0108] In various embodiments, as shown in FIG. **16**, ion guide **1610** is positioned next to ELIT **1620** and on a side of first set of reflectron plates **1621** opposite the lift electrode (pickup electrode **1625**). In various embodiments, guide axis **1601** and ELIT axis **1602** do not need to be coaxial, even in the case of sequential axial injection. Transfer lenses (not shown) between ion guide **1610** and ELIT **1620** can offset the ion beam by several millimeters in order to prevent gas carry-over. Or, ELIT **1620** can be radially offset and the transfer lenses include a pair of deflection electrodes.

[0109] FIG. **18** is a schematic diagram **1800** showing that transfer lenses can be used to offset the ion beam between an ion guide and an ELIT, in accordance with various embodiments. In FIG. **18**, transfer lenses **1830** offset the ion beam between ion guide **1810** and ELIT **1820**.

[0110] FIG. **19** is a schematic diagram **1900** showing that deflection electrodes can be used to offset the ion beam between an ion guide and an ELIT, in accordance with various embodiments. In FIG. **19**, deflection electrodes **1930** offset the ion beam between ion guide **1910** and ELIT **1920**.

[0111] FIG. **20** is a schematic diagram **2000** showing that deflection electrodes can also be used to deflect the ion beam radially between an ion guide and an ELIT, in accordance with various embodiments. In FIG. **20**, deflection electrodes **2030** offset the ion beam between ion guide **2010** and ELIT **2020**.

[0112] Returning to FIG. **16**, during the sequential injection, a fixed potential is applied to first set of reflectron plates **1621**, the lift electrode (pickup electrode **1625**), and second set of reflectron plates **1622**. The ions are sequentially injected into to ELIT **1620** from ion guide **1601** along ELIT axis **1602** and through the holes of first set of reflectron plates **1621**. The ions are focused at the location within the portion of ELIT axis **1602** surrounded by the lift electrode (pickup electrode **1625**) at the same time.

[0113] ELIT **1620** then traps the ions injected into ELIT **1620** by changing the potential applied to the lift electrode (pickup electrode **1625**) that reduces the same ion energy of the ions such that they are unable to overcome the fixed potential barrier of first set of reflectron plates **1621** and second set of reflectron plates **1622**. The ions are then trapped between outermost plates **1651** and **1658** of first set of reflectron plates **1621** and second set of reflectron plates **1622**, respectively.

[0114] An ion guide positioned next to a single detector ELIT that performs in-trap potential-lift is also depict in FIG. **11**.

[0115] Returning to FIG. **16**, in various embodiments, ion guide **1610** can be positioned radially with respect to ELIT **1620** so that guide axis **1601** intersects ELIT axis **1602** at an angle of less than ninety degrees at the same location (focus location) on ELIT axis **1602**. Again, during the sequential injection, a fixed potential is applied to first set of reflectron plates **1621**, the lift electrode (pickup electrode **1625**), and the second set of reflectron plates **1602**. However, in this case, ions are sequentially injected into to ELIT **1620** from ion guide **1610** along guide axis **1601**. The ions are focused at the location within the portion of ELIT axis **1602** surrounded by the lift electrode (pickup electrode **1625**) at the same time. The focus location is also, for example, the intersection (not shown) of guide axis **1601** and the ELIT axis **1602**.

[0116] In various embodiments, ions can be focused anywhere along ELIT axis **1401**. Radial injection of ions into ELIT **1620** allows other mass spectrometry devices to be connected to the input or output of ELIT **1620**. Deflection electrodes (not shown) are used to change the ion trajectory from guide axis **1601** to ELIT axis **1602** by applying dissimilar potentials to the two electrodes. A non-repulsive potential is applied to one deflection electrode and a repulsive potential is applied to the other deflection electrode. Once ions pass through the deflection electrodes, the potentials of both deflection electrodes are made to be equal, thereby capturing ions in ELIT **1620**.

[0117] ELIT **1620** then traps ions in the same fashion as described above in the coaxial case. An ion guide positioned radially with respect to a single detector ELIT that can perform in-trap potential-lift ion capture is depicted in FIG. **14**.

[0118] Returning to FIG. **16**, in various embodiments, ELIT **1620** can be a multi-detector that performs in-trap potential-lift ion capture. ELIT **1620** further includes at least one lift electrode (not shown) positioned along ELIT axis **1602**. In addition to pickup electrode **1625**, ELIT further includes one or more additional pickup electrodes (not shown). The same location (focus location) on ELIT axis **1602** is also a location within a portion of ELIT axis **1602** surrounded by the lift electrode.

[0119] In various embodiments, ion guide **1610** is positioned on the side of first set of reflectron plates **1622** opposite pickup electrode **1625**. During the sequential injection, ions are sequentially injected into ELIT **1620** from ion guide **1610** along ELIT axis **1602**. The ions are focused at a location within the portion of ELIT axis **1602** surrounded by the at least one lift electrode at the same time.

[0120] A multi-detector ELIT traps the ions in the same fashion as a single detector ELIT that performs in-trap potential lift, as described above. An ion guide positioned next to a dual detector ELIT that can perform in-trap potential-lift is depicted in FIG. **10**.

[0121] In various embodiments, an ion guide can also be positioned radially with respect to a multi-detector ELIT that performs in-trap potential lift. The multi-detector ELIT is positioned similarly to single detector **1420** of FIG. **14** and receives injected ions in a similar fashion to single detector

1420. Ions are then trapped in the dual detector ELIT in the same fashion as a single detector ELIT that performs in-trap potential lift, as described above.

[0122] Returning to FIG. **16**, in various embodiments, ELIT **1620** traps the ions along ELIT axis **1602** using mirror-switching after the sequential injection into ELIT **1620** from ion guide **1610**. During the sequential injection, a repulsive potential applied to outermost plate **1651** of first set of reflectron plates **1621** and outermost plate **1658** of second set of reflectron plates **1622** to repulse the ions from ion guide **1610** is changed to a non-repulsive potential at outermost plate **1651** of first set. The ions are sequentially injected into ELIT **1620** from ion guide **1610** along ELIT axis **1602** and through the holes of first set of reflectron plates **1621**. The ions are focused at the same location on ELIT axis **1602** within ELIT **1620** at the same time. The same location on ELIT axis **1602** is a location between plate **1652** of first set of reflectron plates **1621** adjacent to outermost plate **1651** of first set of reflectron plates **1621** and outermost plate **1658** of second set of reflectron plates **1622**. In various embodiments, the same location on ELIT axis **1602** is preferably a location within a portion of ELIT axis **1602** surrounded by pickup electrode **1625** (or the center of ELIT **1620**).

[0123] ELIT **1620** traps the ions injected into ELIT **1620** by reapplying the repulsive potential to outermost plate **1651** of first set of reflectron plates **1621** so that the ions injected into ELIT **1620** are trapped between outermost plate **1651** of first set of reflectron plates **1621** and outermost plate **1658** of second set of reflectron plates **1622**.

[0124] An ion guide positioned next to an ELIT that performs mirror-switching ion capture is also depicted in FIG. **12**.

[0125] In various embodiments, an ion guide can be positioned radially with respect to an ELIT that performs mirror-switching ion capture. Returning to FIG. **16**, ion guide **1610** can be positioned radially with respect to ELIT **1620** so that guide axis **1601** intersects ELIT axis **1602** at an angle of less than ninety degrees at the same location on ELIT axis **1602** within ELIT **1620**.

[0126] During the sequential injection, the ions are sequentially injected along guide axis **1601** into ELIT **1620** from ion guide **1610** and focused at the same location on ELIT axis **1602** within ELIT **1620** at the same time. The same location on ELIT axis **1602**, in this case, is a location between outermost plate **1651** of first set of reflectron plates **1621** and outermost plate **1658** of second set of reflectron plates **1622**. In various embodiments, the same location on ELIT axis **1602** is preferably a location within a portion of ELIT axis **1602** surrounded by pickup electrode **1625** (or the center of ELIT **1620**).

[0127] ELIT **1620** traps the ions injected into ELIT **1620** by applying a repulsive potential to outermost plate **1651** of first set of reflectron plates **1621** and outermost plate **1658** of second set of reflectron plates **1622** that traps the ions injected from ion guide **1610** between outermost plate **1651** of first set of reflectron plates **1621** and outermost plate **1658** of second set of reflectron plates **1622**.

[0128] An ion guide positioned radially with respect to a single detector ELIT that can perform mirror-switching ion capture is depicted in FIG. **14**.

[0129] In various embodiments, the system of FIG. **16** further includes one or more voltage sources **1640**. The one or more voltage sources **1640** apply different voltages to one or more electrodes of ELIT **1620** and ion guide **1610**.

[0130] In various embodiments, processor **1630** is used to control or provide instructions to ion guide **1610** and ELIT **1620** and to analyze data collected. Processor **1630** controls or provides instructions by, for example, controlling one or more voltage sources **1640**. Processor **1630** can also control one or more current or pressure sources (not shown). Alternatively, processor **1630** can directly apply currents or voltages. Processor **1630** can be a separate device as shown in FIG. **16** or can be a processor or controller of one or more devices of a mass spectrometer (not shown). Processor **1630** can be, but is not limited to, a controller, a computer, a microprocessor, the computer system of FIG. **1**, or any device capable of sending and receiving control signals and data.

[0131] Method for Injecting Ions into an ELIT

[0132] FIG. **21** is a flowchart showing a method **2100** for sequentially injecting ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT, in accordance with various embodiments.

[0133] In step **2110** of method **2100**, an ion guide defining a guide axis is instructed to receive ions along the guide axis from an ion beam of a mass spectrometer using a processor.

[0134] In step **2120**, the ion guide is instructed to apply a potential profile that includes a pseudopotential well to the ions along the guide axis using an ion control field that includes a component for restraining movement of the ions normal to the guide axis and a component for controlling the movement of the ions parallel to the guide axis using the processor.

[0135] In step **2130**, the ion guide is instructed to sequentially inject the ions with the same ion energy and in order of m/z value into an ELIT aligned along an ELIT axis to focus the ions irrespective of m/z value at the same location on the ELIT axis within the ELIT at the same time by varying a magnitude of the pseudopotential well using the processor.

[0136] Computer Program Product for Injecting Ions into an ELIT

[0137] In various embodiments, computer program products include a tangible computer-readable storage medium whose contents include a program with instructions being executed on a processor so as to perform a method a method for sequentially injecting ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT. This method is performed by a system that includes one or more distinct software modules.

[0138] FIG. **22** is a schematic diagram of a system **2200** that includes one or more distinct software modules that perform a method a method for sequentially injecting ions into an ELIT of a mass spectrometer so that ions with different m/z values are focused at the same location at the same time in the ELIT, in accordance with various embodiments. System **2200** includes a control module **2210**.

[0139] Control module **2210** instructs an ion guide defining a guide axis to receive ions along the guide axis from an ion beam of a mass spectrometer. Control module **2210** instructs the ion guide to apply a potential profile that includes a pseudopotential well to the ions along the guide axis using an ion control field. The ion control field includes a component for restraining movement of the ions normal to the guide axis and a component for controlling the movement of the ions parallel to the guide axis. Control module **2210** instructs the ion guide to sequentially inject the ions with the same ion energy and in order of m/z value into an ELIT aligned along an ELIT axis to focus the ions irrespective of m/z value at the same location on the ELIT axis within the ELIT at the same time by varying a magnitude of the pseudopotential well.

[0140] While the present teachings are described in conjunction with various embodiments, it is not intended that the present teachings be limited to such embodiments. On the contrary, the present teachings encompass various alternatives, modifications, and equivalents, as will be appreciated by those of skill in the art.

[0141] Further, in describing various embodiments, the specification may have presented a method and/or process as a particular sequence of steps. However, to the extent that the method or process does not rely on the particular order of steps set forth herein, the method or process should not be limited to the particular sequence of steps described. As one of ordinary skill in the art would appreciate, other sequences of steps may be possible. Therefore, the particular order of the steps set forth in the specification should not be construed as limitations on the claims. In addition, the claims directed to the method and/or process should not be limited to the performance of their steps in the order written, and one skilled in the art can readily appreciate that the sequences may be varied and still remain within the spirit and scope of the various embodiments.

What is claimed is:

1. A system for sequentially injecting ions into an electrostatic linear ion trap (ELIT) of a mass spectrometer so that ions with different mass-to-charge ratio (m/z) values are focused at a same location at a same time in the ELIT, comprising:
  an ELIT that includes
    a first set of reflectron plates with holes in the center that is aligned along an ELIT axis and
    a second set of reflection plates with holes in the center that is aligned along the ELIT axis; and
  an ion guide defining a guide axis that
    receives ions along the guide axis from an ion beam of a mass spectrometer,
    applies a potential profile that includes a pseudopotential well to the ions along the guide axis using an ion control field that includes a component for restraining movement of the ions normal to the guide axis and a component for controlling the movement of the ions parallel to the guide axis, and
    sequentially injects the ions into the ELIT with a same ion energy and in order of m/z value to focus the ions irrespective of m/z value at a same location on the ELIT axis within the ELIT at a same time by varying a magnitude of the pseudopotential well.

2. The system of claim **1**, wherein the ELIT traps the ions along the ELIT axis using in-trap potential-lift after the sequential injection into the ELIT from the ion guide.

3. The system of claim **2**, wherein the ELIT is a single detector ELIT and wherein the same location on the ELIT axis within the ELIT comprises a location within a portion of the ELIT axis surrounded by a lift electrode.

4. The system of claim **3**,
  wherein the ion guide is positioned on a side of the first set of reflectron plates opposite the lift electrode,
  wherein, during the sequential injection, a fixed potential is applied to the first set of reflectron plates, the lift electrode, and the second set of reflectron plates, the ions are sequentially injected into the ELIT from the ion guide along the ELIT axis and through the holes of the first set of reflectron plates, and the ions are focused at the location within the portion of the ELIT axis surrounded by the lift electrode at the same time, and
  wherein the ELIT traps the ions injected into the ELIT by applying a potential to the lift electrode that reduces the same ion energy of the ions low enough to be unable to overcome the fixed potential of the first set of reflectron plates and the second set of reflectron plates and trapping the ions between the outermost plates of the first set and the second set.

5. The system of claim **3**,
  wherein the ion guide is positioned radially with respect to the ELIT so that the guide axis intersects the ELIT axis at an angle of less than ninety degrees at the same location on the ELIT axis,
  wherein two or more deflection electrodes are used to change the ion trajectory from the guide axis to the ELIT axis by applying dissimilar potentials to the two or more deflection electrodes, a non-repulsive potential is applied to at least one deflection electrode and a repulsive potential is applied to at least one other deflection electrode, and, once ions pass through d the two or more deflection electrodes, the potential of at least one deflection electrode and the at least one other deflection electrode are made to be equal,
  wherein, during the sequential injection, a fixed potential is applied to the first set of reflectron plates, the lift electrode, and the second set of reflectron plates, the ions are sequentially injected into the ELIT from the ion guide along the guide axis, and the ions are focused at the location within the portion of the ELIT axis surrounded by the lift electrode at the same time, and
  wherein the ELIT traps the ions injected into the ELIT by applying a potential to the lift electrode that reduces the same ion energy of the ions low enough to be unable to overcome the fixed potential of the first set of reflectron plates and the second set of reflectron plates and trapping the ions between the outermost plates of the first set and the second set.

6. The system of claim **2**, wherein the ELIT is a multi-detector ELIT, wherein the ELIT further includes at least one lift electrode and two or more pickup electrodes positioned along the ELIT axis and wherein the same location on the ELIT axis within the ELIT comprises a location within a portion of the ELIT axis surrounded by the lift electrode.

7. The system of claim **6**,
  wherein the ion guide is positioned on a side of the first set of reflectron plates,
  wherein, during the sequential injection, a fixed potential is applied to the first set of reflectron plates, the lift electrode, and the second set of reflectron plates, the ions are sequentially injected into the ELIT from the ion guide along the ELIT axis, through the holes of the first set of reflectron plates, and the ions are focused at the location within the portion of the ELIT axis surrounded by the lift electrode at the same time, and
  wherein the ELIT traps the ions injected into the ELIT by applying a potential to the lift electrode that reduces the same ion energy of the ions low enough to be unable to

overcome the fixed potential of the first set of reflectron plates and the second set of reflectron plates and trapping the ions between the outermost plates of the first set and the second set.

8. The system of claim **6**,

wherein the ion guide is positioned radially with respect to the ELIT so that the guide axis intersects the ELIT axis at an angle of less than ninety degrees at the same location on the ELIT axis,

wherein two or more deflection electrodes are used to change the ion trajectory from the guide axis to the ELIT axis by applying dissimilar potentials to the two or more deflection electrodes, a non-repulsive potential is applied to at least one deflection electrode and a repulsive potential is applied to at least one other deflection electrode, and, once ions pass through d the two or more deflection electrodes, the potential of at least one deflection electrode and the at least one other deflection electrode are made to be equal,

wherein, during the sequential injection, a fixed potential is applied to the first set of reflectron plates, the lift electrode, and the second set of reflectron plates, the ions are sequentially injected into the ELIT from the ion guide along the guide axis, and the ions are focused at the location within the portion of the ELIT axis surrounded by the lift electrode at the same time, and

wherein the ELIT traps the ions injected into the ELIT by applying a potential to the lift electrode that reduces the same ion energy of the ions low enough to be unable to overcome the fixed potential of the first set of reflectron plates and the second set of reflectron plates and trapping the ions between the outermost plates of the first set and the second set.

9. The system of claim **1**, wherein the ELIT traps the ions along the ELIT axis using mirror-switching after the sequential injection into the ELIT from the ion guide.

10. The system of claim **9**,

wherein the ion guide is positioned on a side of the first set of reflectron plates,

wherein, during the sequential injection, a repulsive potential applied to an outermost plate of the first set of reflectron plates and an outermost plate of the second set of reflectron plates to repulse the ions from the ion guide is changed to a non-repulsive potential at the outermost plate of the first set, the ions are sequentially injected into the ELIT from the ion guide along the ELIT axis and through the holes of the first set of reflectron plates, and the ions are focused at the same location on the ELIT axis within the ELIT at the same time,

wherein the same location on the ELIT axis comprises a location between a plate of the first set adjacent to the outermost plate of the first set and the outermost plate of the second set, and

wherein the ELIT traps the ions injected into the ELIT by reapplying the repulsive potential to the outermost plate of the first set of reflectron plates so that the ions injected into the ELIT are trapped between the outermost plate of first set and the outermost plate of the second set.

11. The system of claim **10**, wherein the location between a plate of the first set of reflectron plates adjacent to the outermost plate of the first set of reflectron plates and the outermost plate of the second set of reflectron plates comprises a location within a portion of the ELIT axis surrounded by a pickup electrode.

12. The system of claim **9**,

wherein the ion guide is positioned radially with respect to the ELIT so that the guide axis intersects the ELIT axis at an angle of less than ninety degrees at the same location on the ELIT axis within the ELIT,

wherein two or more deflection electrodes are used to change the ion trajectory from the guide axis to the ELIT axis by applying dissimilar potentials to the two or more deflection electrodes, a non-repulsive potential is applied to at least one deflection electrode and a repulsive potential is applied to at least one other deflection electrode, and, once ions pass through d the two or more deflection electrodes, the potential of at least one deflection electrode and the at least one other deflection electrode are made to be equal,

wherein, during the sequential injection, the ions are sequentially injected along the guide axis into the ELIT from the ion guide and focused at the same location on the ELIT axis within the ELIT at the same time,

wherein the same location on the ELIT axis within the ELIT comprises a location between the outermost plate of the first set of reflectron plates and the outermost plate of the second set of reflectron plates, and

wherein the ELIT traps the ions injected into the ELIT by applying a repulsive potential to an outermost plate of the first set and an outermost plate of the second set that traps the ions injected from the ion guide between the outermost plates of the first set and the second set.

13. The system of claim **12**, wherein the location between the outermost plate of the first set of reflectron plates and the outermost plate of the second set of reflectron plates comprises a location within a portion of the ELIT axis surrounded by a pickup electrode.

14. A method for sequentially injecting ions into an electrostatic linear ion trap (ELIT) of a mass spectrometer so that ions with different mass-to-charge ratio (m/z) values are focused at a same location at a same time in the ELIT, comprising:

instructing an ion guide defining a guide axis to receive ions along the guide axis from an ion beam of a mass spectrometer using a processor;

instructing the ion guide to apply a potential profile that includes a pseudopotential well to the ions along the guide axis using an ion control field that includes a component for restraining movement of the ions normal to the guide axis and a component for controlling the movement of the ions parallel to the guide axis using the processor, and

instructing the ion guide to sequentially inject the ions with a same ion energy and in order of m/z value into an ELIT aligned along an ELIT axis to focus the ions irrespective of m/z value at a same location on the ELIT axis within the ELIT at a same time by varying a magnitude of the pseudopotential well using the processor.

15. A computer program product, comprising a non-transitory and tangible computer-readable storage medium whose contents include a program with instructions being executed on a processor to perform a method for sequentially injecting ions into an electrostatic linear ion trap (ELIT) of a mass spectrometer so that ions with different mass-to-charge ratio (m/z) values are focused at a same location at a same time in the ELIT, comprising:

providing a system, wherein the system comprises one or more distinct software modules, and wherein the distinct software modules comprise a control module;

instructing an ion guide defining a guide axis to receive ions along the guide axis from an ion beam of a mass spectrometer using the control module;

instructing the ion guide to apply a potential profile that includes a pseudopotential well to the ions along the guide axis using an ion control field that includes a component for restraining movement of the ions normal to the guide axis and a component for controlling the movement of the ions parallel to the guide axis using the control module, and

instructing the ion guide to sequentially inject the ions with a same ion energy and in order of m/z value into an ELIT aligned along an ELIT axis to focus the ions irrespective of m/z value at a same location on the ELIT axis within the ELIT at a same time by varying a magnitude of the pseudopotential well using the control module.

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