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Via A. Gramsci, 70
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c.a. Dott. Marco Fidani

Rodano (MI), 11 Ottobre 2018

DICHIARAZIONE DI UNICITA'

Si dichiara che:

Lo spettrometro di massa a filtro Quadrupolare accoppiato ad un sistema FT MS basato sulla nuova tecnologia Orbitrap, denominato Q-EXACTIVE Plus presenta le seguenti caratteristiche che lo rendono unico nel mercato della Spettrometria di Massa.

Spettrometro di Massa a Trasformata di Fourier (FTMS) funzionate in base ad un nuovo concetto brevettato da Thermo Fisher, che non utilizza campi magnetici (generati da magneti a superconduzione con conseguenti sistemi criogenici), radiofrequenze o misura di tempi di volo (TOF) per separare gli ioni di diverso valore di massa/carica come negli spettrometri attualmente in commercio, ma utilizza un (semplice) campo elettrostatico applicato ad un elettrodo centrale intorno al quale ruotano in modo Radiale ed Assiale gli ioni stessi.

La determinazione del rapporto Massa su Carica (m/z) degli ioni avviene misurando nel tempo la corrente generata dalla movimento assiale degli ioni medesimi.

La Trasformata di Fourier viene utilizzata per convertire il segnale acquisito nel tempo in quello delle diverse frequenze ed intensità che lo compongono da cui viene calcolata la massa e la quantità degli ioni.

La risoluzione dello spettro di massa ottenuto dipende dalla durata del tempo di osservazione senza perdita di intensità del segnale al suo aumentare.

Lo spettrometro di massa Q Exactive Plus e' in grado di garantire una Risoluzione massima di 140.000 FWHM misurata a m/z 200

La tecnologia Orbitrap è protetta dai seguenti brevetti:

- Orbitrap Patent Number US 6,872,938 B2
- Orbitrap Patent Number US 5,886,346

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Inoltre lo Spettrometro di Massa Q Exactive possiede le seguenti caratteristiche uniche aggiuntive:

Possibilità diverse di frammentazione:

- HCD (Higher Energy Collision Dissociation) nella cella quadrupolare dell'Orbitrap con generazione di uno spettro di frammentazione.

Possibilità di isolamento dello ione precursore in alta risoluzione.

- HRI con isolamento pari a 0.4 amu.
- Data Dependent ScanTM
  Possibilità di acquisire spettri MS-Full Scan e MS/MS.

Si dichiara inoltre che l'unica società ufficialmente riconosciuta dalla casa madre autorizzata a rivendere la propria strumentazione, nel dettaglio gli spettrometri di massa a filtro quadrupolare accoppiati ad un sistema FT-MS basati sulla nuova tecnologia Orbitrap e denominati Q Exactive Plus , è unicamente ed esclusivamente Thermo Fisher Scientific S.p.a. su tutto il territorio nazionale.

Thermo Fisher Scientific S.p.A.
L'AMMINISTRATORE DELEGATO

US006872938B2

(12) United States Patent
Makarov et al.

(10) **Patent No.: US 6,872,938 B2**

(45) **Date of Patent: Mar. 29, 2005**

(54) **MASS SPECTROMETRY METHOD AND APPARATUS**

(75) Inventors: **Alexander Makarov**, Cheshire (GB); **Mark E. Hardman**, Manchester (GB); **Jae C. Schwartz**, San Jose, CA (US); **Michael W. Senko**, Sunnyvale, CA (US)

(73) Assignee: **Thermo Finnigan LLC**, San Jose, CA (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.

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PCT Pub. Date: **Oct. 3, 2002**

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(52) **U.S. Cl.** **250/281**; 250/292; 250/287; 250/288

(58) **Field of Search** 250/281, 292, 250/287, 288

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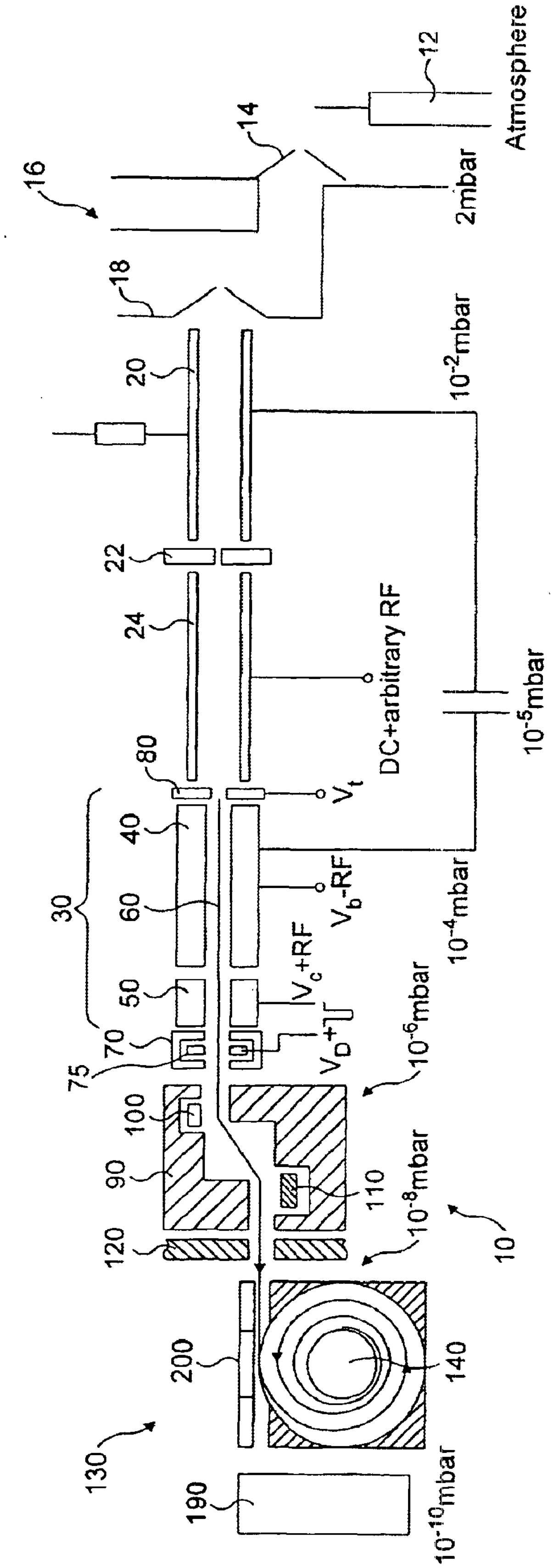
Primary Examiner—John R. Lee
Assistant Examiner—Zia R. Hashmi
(74) *Attorney, Agent, or Firm*—Haynes and Boone, LLP

(57) **ABSTRACT**

A mass spectrometer **10** comprises an ion source **12** which generates nebulized ions which enter an ion cooler **20** via an ion source block **16**. Ions within a window of m/z of interest are extracted via a quadrupole mass filter **24** and passed to a linear trap **30**. Ions are trapped in a potential well in the linear trap **30** and are bunched at the bottom of the potential well adjacent an exit segment **50**. Ions are gated out of the linear trap **30** into an electrostatic ion trap **130** and are detected by a secondary electron multiplier **10**.

By bunching the ions in the linear trap **30** prior to ejection, and by focussing the ions in time of flight (TOF) upon the entrance of the electrostatic trap **130**, the ions arrive at the electrostatic trap **130** as a convolution of short, energetic packets of similar m/z. Such packets are particularly suited to an electrostatic trap because the FWHM of each packet's TOF distribution is less than the period of oscillation of those ions in the electrostatic trap.

50 Claims, 8 Drawing Sheets



12
Atmosphere
14
16
2mbar
18
20
10^{-2}mbar
22
24
DC+arbitrary RF
10^{-5}mbar
80
V_t
30
40
60
V_b-RF
10^{-4}mbar
50
V_c+RF
70
75
V_D+
10^{-6}mbar
100
90
110
10^{-8}mbar
120
10
200
140
130
190
10^{-10}mbar

FIG. 1

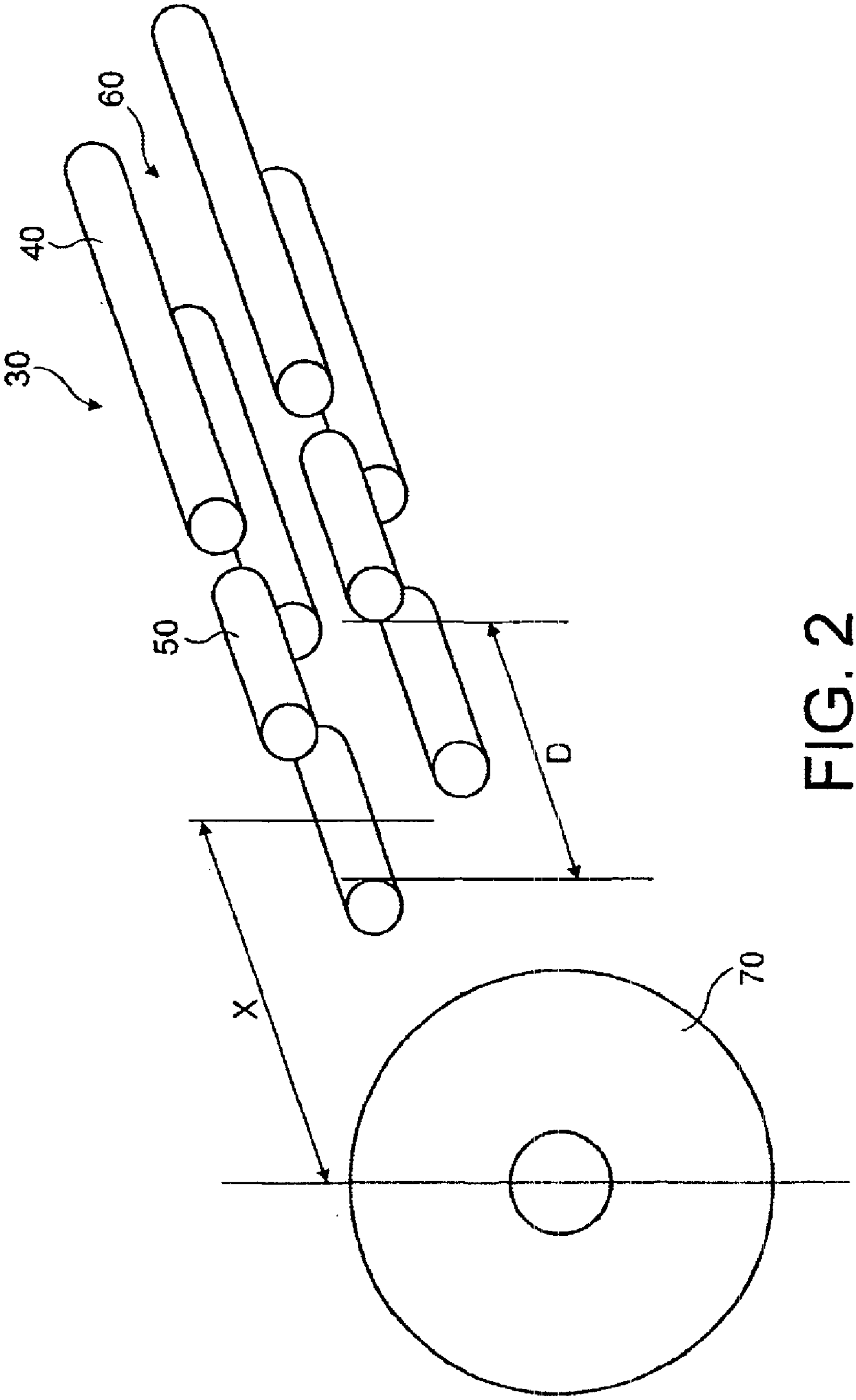


FIG. 2

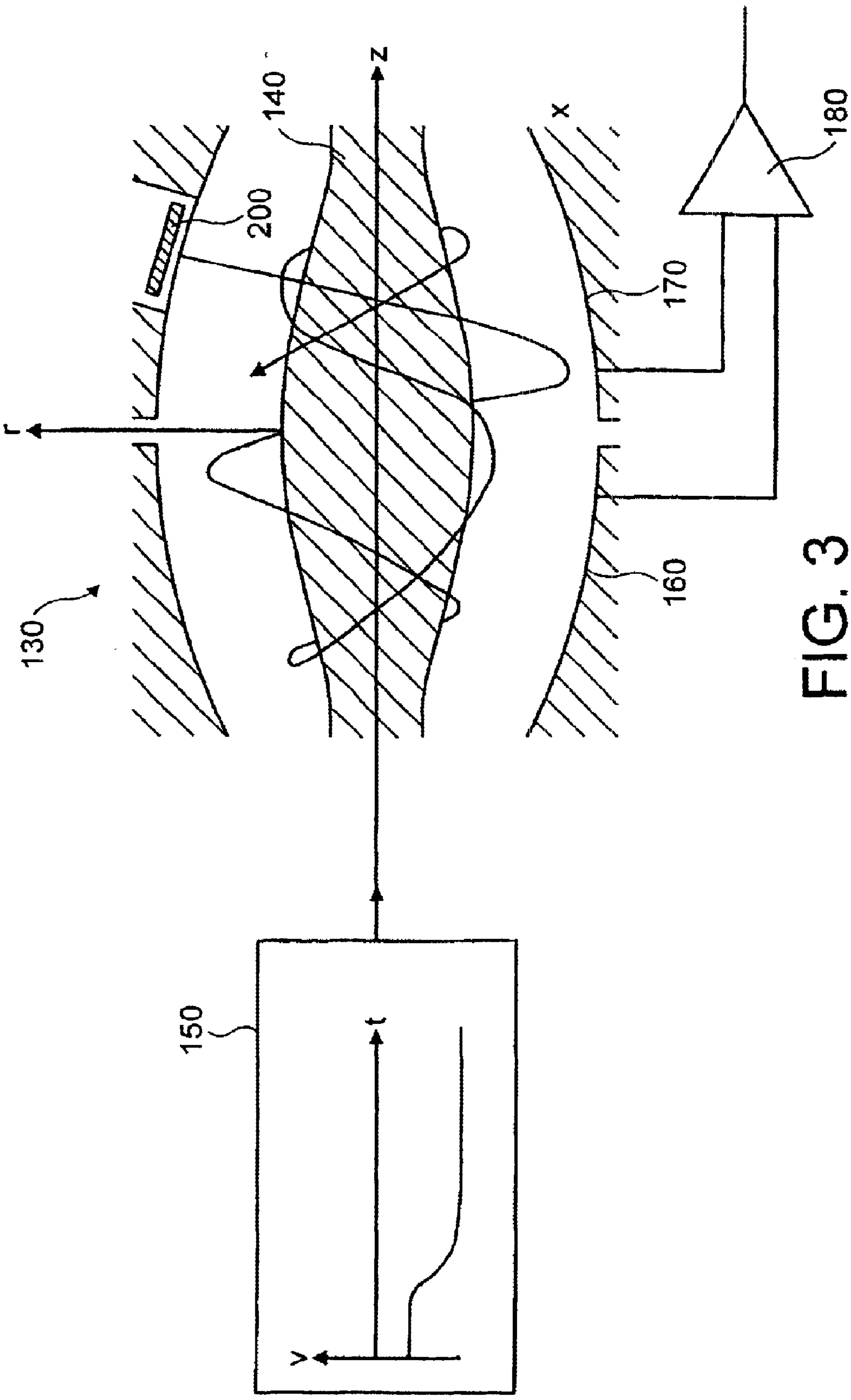
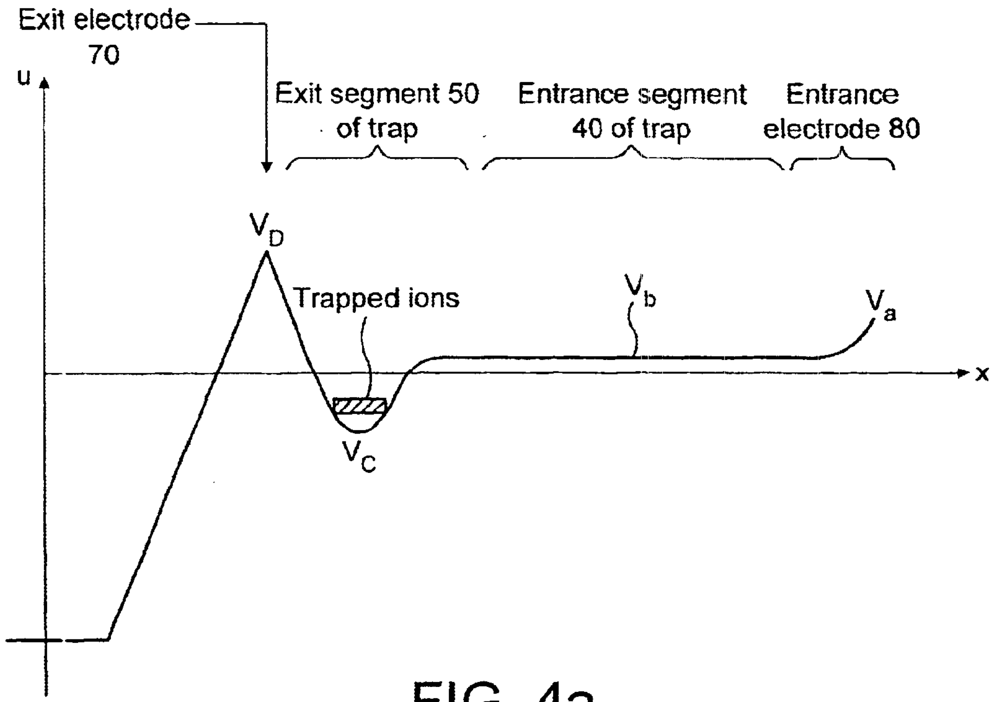
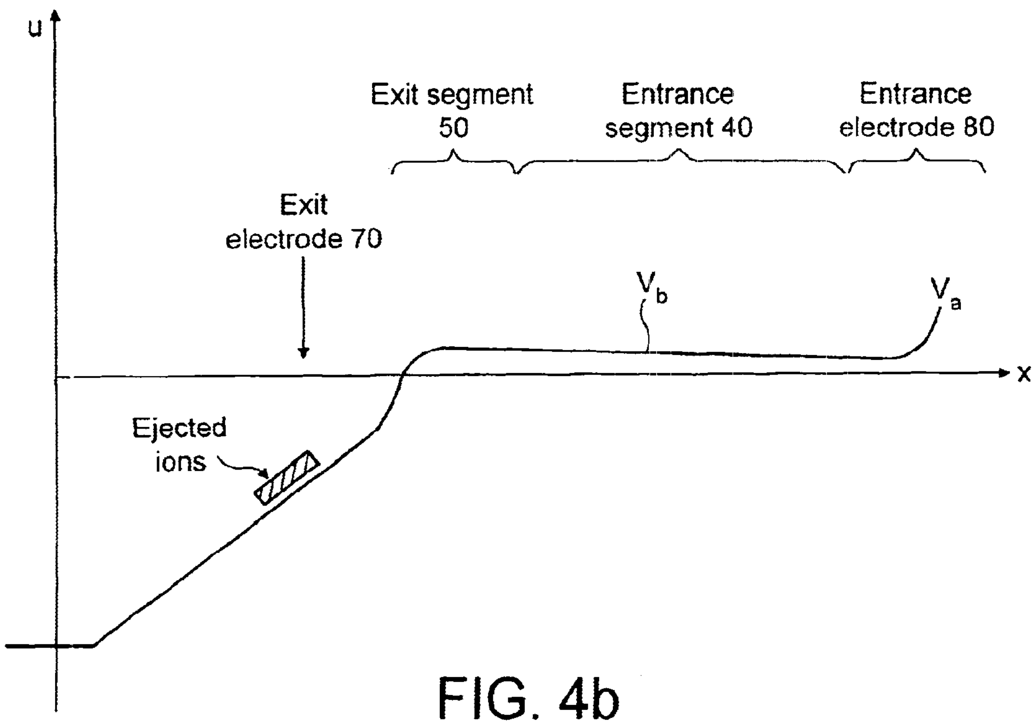


FIG. 3



Exit electrode
70
u
Exit segment 50
of trap
Entrance segment
40 of trap
Entrance
electrode 80
V_D
Trapped ions
V_b
V_a
x
V_C

FIG. 4a



u
Exit segment
50
Entrance
segment 40
Entrance
electrode 80
Exit
electrode 70
V_b
V_a
x
Ejected
ions

FIG. 4b

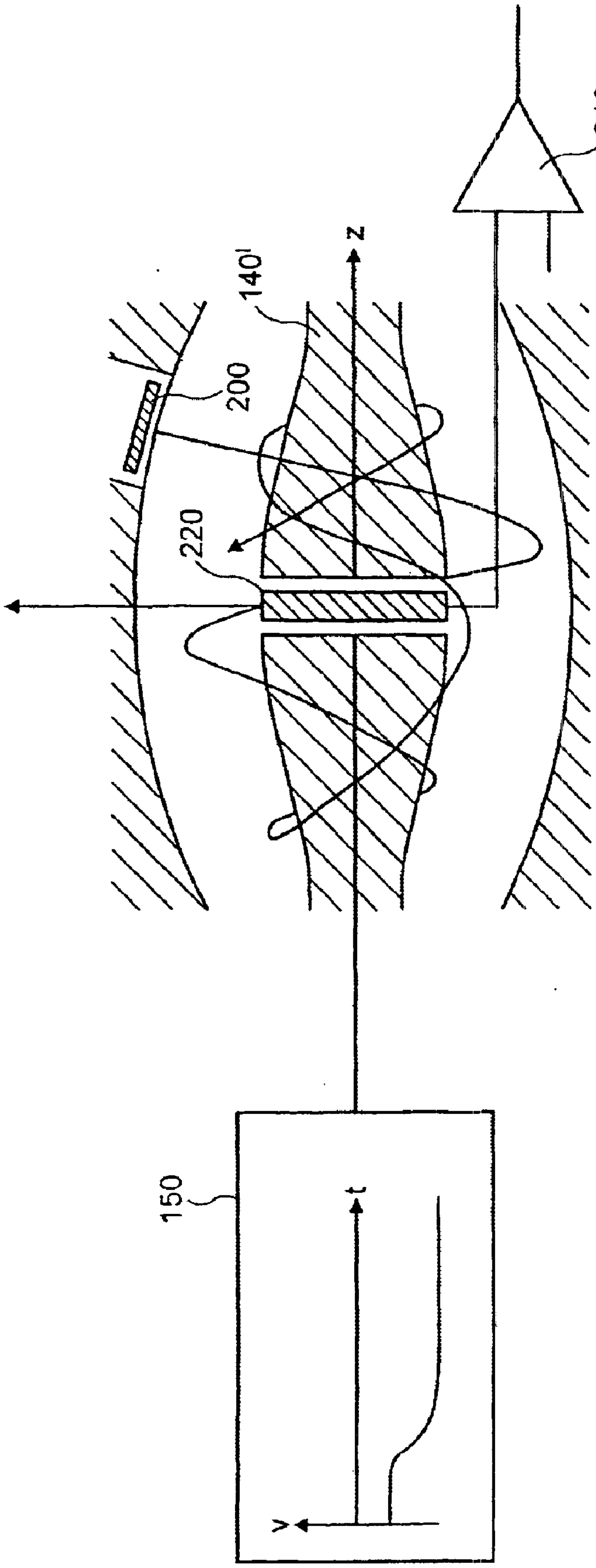


FIG. 5

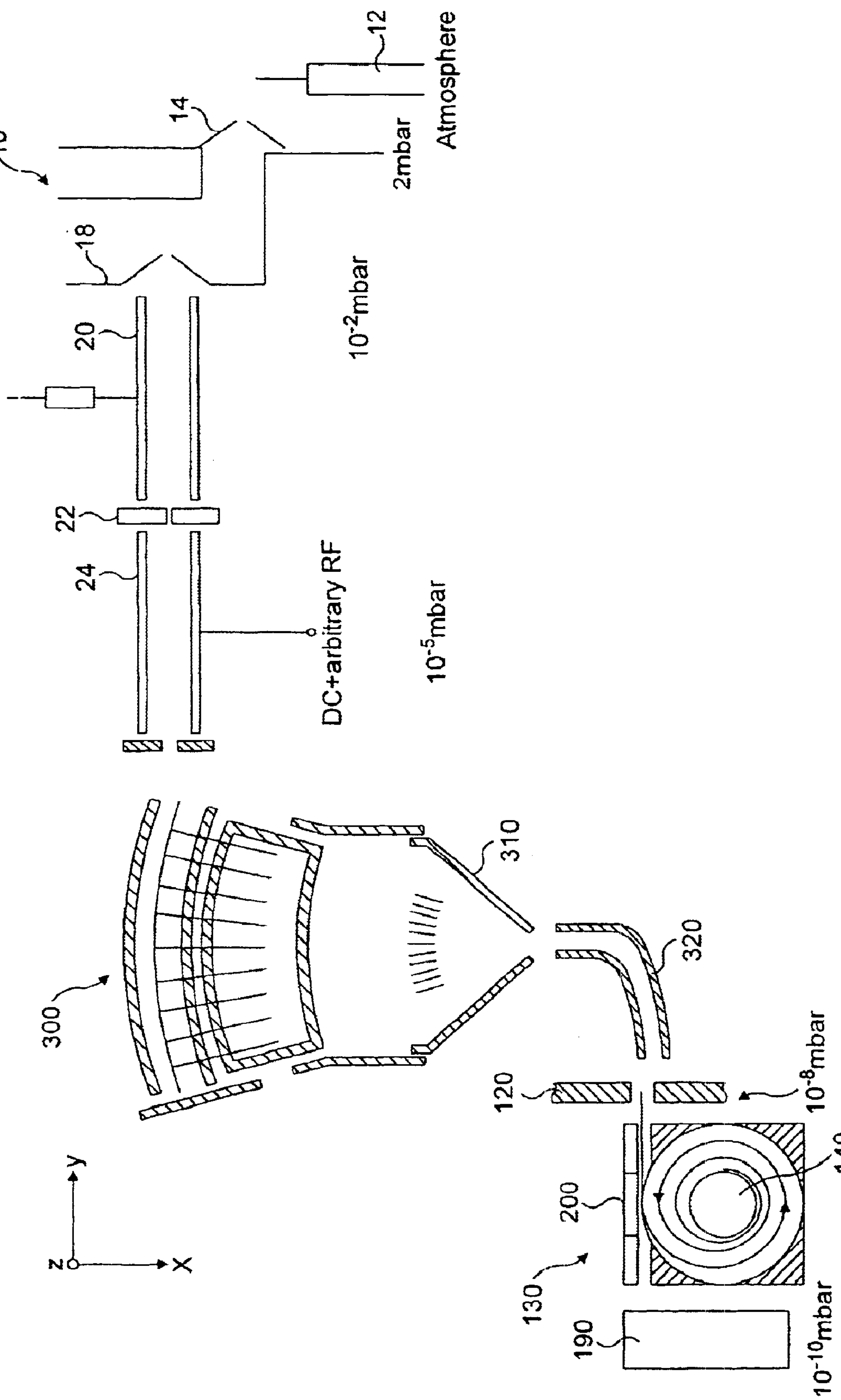
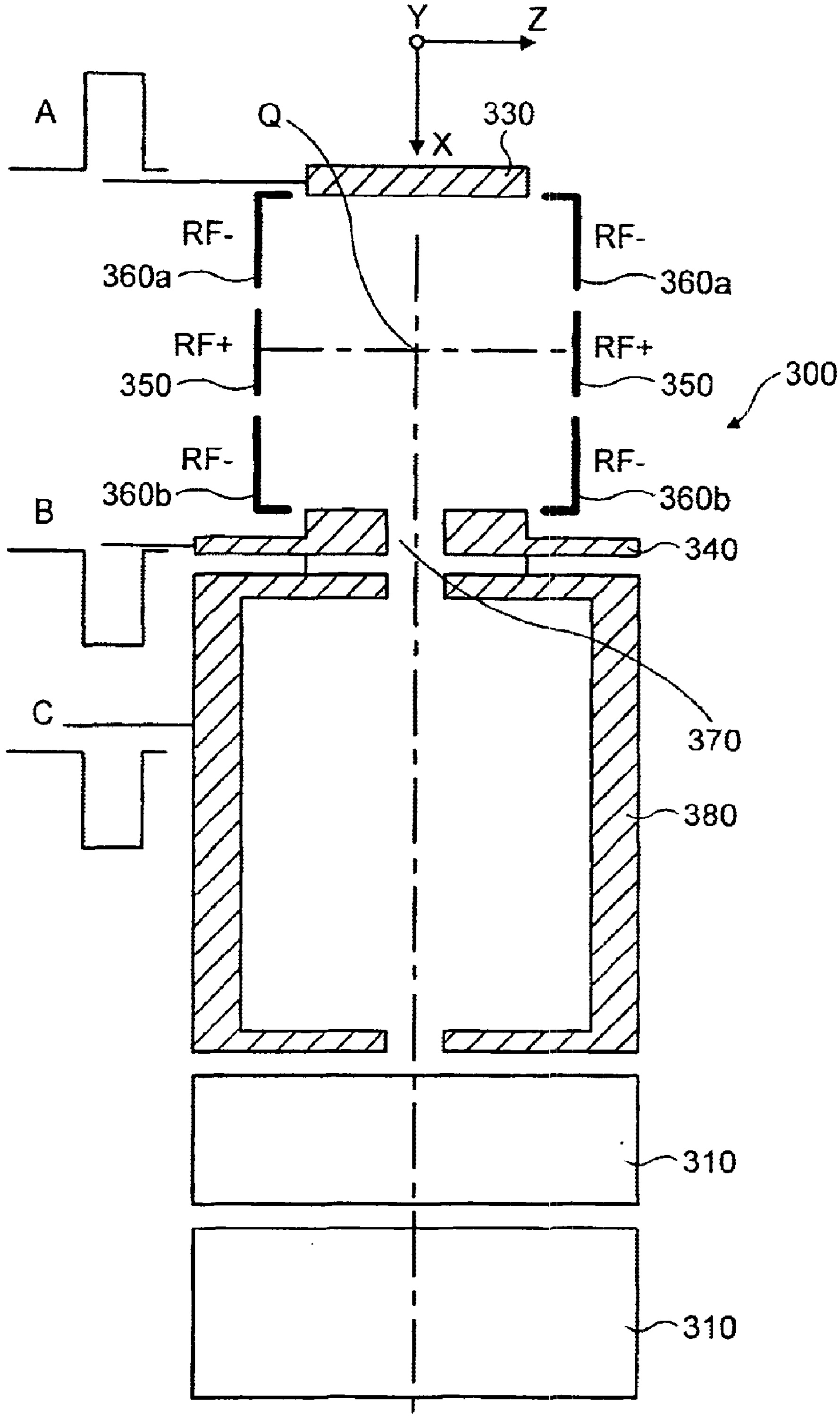

16
14
12
Atmosphere
2mbar
18
10^{-2}mbar
20
22
24
DC+arbitrary RF
10^{-5}mbar
300
310
320
120
10^{-8}mbar
200
140
130
190
10^{-10}mbar
y
z
x

FIG. 6



Y
Z
X
A
Q
330
RF-
360a
RF-
360a
RF+
350
RF+
350
300
RF-
360b
RF-
360b
B
340
C
370
380
310
310

FIG. 7

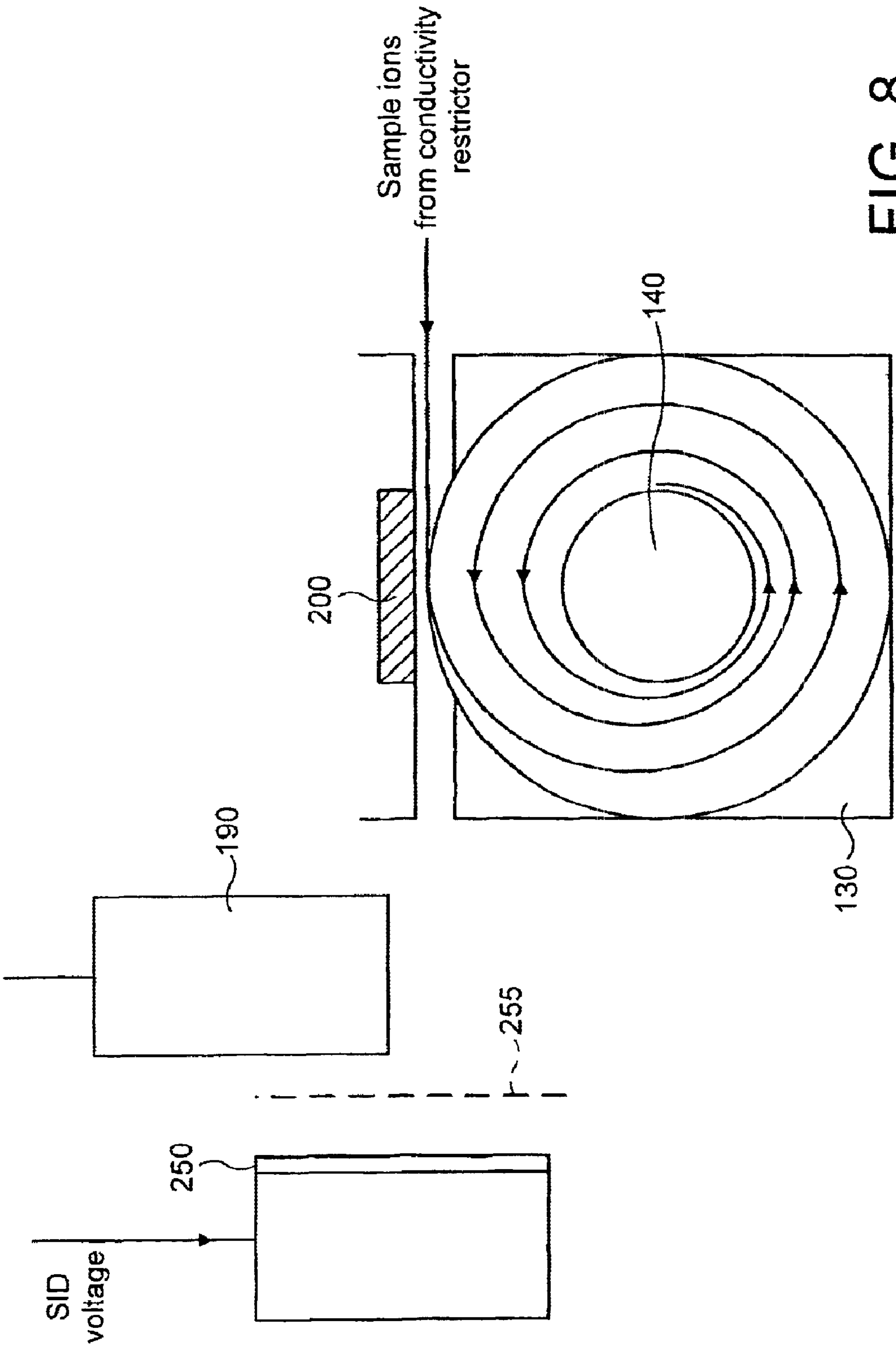

Sample ions
from conductivity
restrictor
140
200
190
130
255
250
SID
voltage

FIG. 8

MASS SPECTROMETRY METHOD AND APPARATUS

FIELD OF INVENTION

This invention relates to a method and an apparatus of mass spectrometry, and in particular to a method and an apparatus for storage and injection of ions into an electrostatic ion trap.

BACKGROUND OF THE INVENTION

Mass spectrometers have been used to analyse a wide range of materials, including organic substances such as pharmaceutical compounds, environmental compounds and biomolecules. They are particularly useful, for example, for DNA and protein sequencing. In such applications, there is an ever increasing desire for high mass accuracy, as well as high resolution of analysis of sample ions by the mass spectrometer, notwithstanding the short time frame of modern separation techniques such as gas chromatography/mass spectrometry (GC/MS), liquid chromatography/mass spectrometry (LC/MS) and so forth.

One of the new directions in the field of mass spectrometry is the development of mass analysers where ions are dynamically trapped in an electrostatic field. Broadly, these may be divided into two classes: those that employ frequency analysis by image current detection, as disclosed in U.S. Pat. No. 5,880,466 and U.S. Pat. No. 5,886,346, and those that employ time of flight (TOF) separation and ion detection by secondary electron conversion, as is disclosed, for example by H. Wollnik, in J. Mass Spectrom. Ion Proc. (1994), vol. 131, at pages 387–407, and by C. Piadyasa et al., in Rapid Commun. Mass Spectrom. (1999), vol. 13 at pages 620–624. Although the trap fields may be ramped at the beginning of the mass scan, they are typically held very stable during the detection, or TOF separation of ions, and so each of the foregoing mass analysers may be regarded as electrostatic traps (ESTs).

Such EST mass analysers can achieve high and even ultra-high mass resolutions (in excess of 100,000), thus allowing more accurate determination of ion masses. However, they all operate using an inherently pulsed technique and as such the task of coupling to any external continuous ion source is a serious problem.

To improve duty cycle and sensitivity, it is possible to use an external collision quadrupole ion trap for ion cooling and storage between injections. This technique has proved particularly successful when combined with other inherently pulsed techniques such as TOF mass analysis as is described by S. Michael et al., in Rev. Sci. Instrum. (1992) vol. 63, pages 4277 to 4284. Here, ions are accumulated in the trap. As suggested in U.S. Pat. No. 5,572,022, it is possible to control the number of ions in the trap to reduce space-charge effects. Once ions have been stored in the trap, they can be pulsed into the TOF mass analyser by applying high voltages to the (normally grounded) end caps of the trap. In U.S. Pat. No. 5,569,917, the ions are given a simultaneous "push" out of the trap and a "suck" from the TOF mass analyser, so as to improve the efficiency of ion injection into the analyser. The spatially spread ion beam is focussed into a tight pack in the "object" plane of the TOF mass analyser.

Despite these improvements, quadrupole ion traps are still currently a relatively inefficient technique for injecting ions into a mass analyser (down to a few percent), and they also suffer from low space charge capacity due to the limited trap volume.

One approach that has been taken to address these problems is to employ a different type of collisonal storage device known as a linear trap (LT) or RF multipole trap. U.S. Pat. No. 5,179,278 shows such an arrangement, wherein a two-dimensional multipole RF field is generated. The trap of U.S. Pat. No. 5,179,278 is limited by end lenses. Alternatively, the poles of the trap may be split into sections as is shown in U.S. Pat. No. 5,420,425. Both split poles and end caps can be employed together. The elevated voltages on the end lenses or sections limit the ion movement along the axis whilst the RF voltage provides a quasi-potential well in the radial direction. If ions lose enough energy during the first passes through the multipole, then they may be trapped in it and squeezed towards the axis during further collisions. The number of ions in the trap can be controlled using a short pre-scan, a technique disclosed in the above-referenced U.S. Pat. No. 5,572,022. Nevertheless, to inject ions from the LT into the next stage of analysis, the voltage is lowered on the exit lens and the ions in the LT are allowed to flow out of the multipole. This flow typically lasts up to hundreds or even thousands of microseconds. These time scales are compatible with the injection times for quadrupole ion traps (as disclosed in the above-referenced U.S. Pat. No. 5,179,278) or for Fourier Transform Ion Cyclotron Resonance (FTICR) as set out by M. Senko et al in JASMS, (1997), volume 8, pages 970–976. The time scales are also suitable for orthogonal acceleration TOF mass spectrometry, see for example U.S. Pat. No. 6,011,259, U.S. Pat. No. 6,020,586, and WO99/30350.

Segmented construction of the poles in the LT may be employed, as set out by M. Belov et al, in Analytical Chemistry (2001) volume 73, pages 253–261, to reduce the injection time down to about 300–400 microseconds. The segmented construction of the LT provides an axial field which causes ions to be displaced towards the exit lens.

Even so, such injection times are too long for an electrostatic trap. This is because ESTs require high ion energies (typically 1–2 keV per charge) to achieve dynamic trapping. If injection takes place over hundreds of microseconds, at such energies the process may last for hundreds of ion reflections. Without any collisional cooling inside the electrostatic trap, ion stability may be compromised.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and an apparatus which alleviates these problems with the prior art. In particular, it is an object to provide a method and an apparatus which provides for adequate storage of ions prior to injection of these ions into an electrostatic trap over a timescale compatible with such a device.

According to a first aspect of the present invention, there is provided a method of injection of sample ions into an electrostatic trap, comprising the steps of: (a) generating a plurality of sample ions to be analysed, each of which has a mass-to-charge ratio m/z; (b) receiving the sample ions through a storage device entrance in an ion storage device having a plurality of storage device poles; (c) supplying a trapping voltage to the storage device so as to trap at least a proportion of the received sample ions within a volume ρ in the storage device, during at least a part of a trapping period, the thus trapped ions each having a kinetic energy E_k such that there is an average kinetic energy $\overline{E}_k$ of the ions in the volume ρ during the trapping period or the said part thereof; (d) supplying a release voltage to the storage device so as to controllably release at least some of the said sample ions contained within the said volume of the storage device from a storage device exit, the release voltage being of a magnitude such that the potential difference then experienced by the ions across the volume ρ is greater than the said average kinetic energy $\overline{E}_k$ during the trapping period or said part thereof, and further wherein the release voltage is such that the strength of the electric field generated thereby at any first point across the volume ρ, upon application of the said release voltage, is no more than 50% greater or smaller than the strength of the electric field generated thereby at any other second point across the volume ρ; (e) receiving those sample ions released from the storage device exit according to the criteria of step (d) through an entrance of an electrostatic trap having a plurality of trapping electrodes, the ions arriving as a convolution of bunched time of flight distributions for each m/z, each distribution having a full width at half maximum (FWHM); and (f) trapping the received sample ions within the electrostatic trap by applying a potential to the electrodes such that the sample ions describe movement having periodic oscillations in at least one direction.

The method of the present invention proposes particular restrictions on the release potential supplied to the storage device which ensures that groups of ions of a given m/z arrive as a tightly focussed 'bunch' at or adjacent the electrostatic trap. The two conditions are, respectively, that the electric field experienced by the ions upon leaving the storage device is relatively uniform and that the potential drop experienced by the ions upon release is larger than the average thermal (kinetic) energy of the ions when trapped in the storage device, and preferably much larger.

The first condition is a consequence of the effective focussing of ions in time of flight from the storage device and into the electrostatic trap. The focal length, L, is given by $L=\alpha V/E$, where V is the final energy of the ions when released from the storage device, E is the electric field strength, and α is a constant. If the electric field is non-uniform, therefore, along the volume ρ, then ions of the same m/z will be focussed at different lengths L and will not arrive in the same tightly focussed bunch. A variation in the electric field strength of no more than about 30%–50% is preferred.

The second criterion ensures that the thermal energy (i.e., the kinetic energy) of the trapped ions is less than and preferably insignificant relative to the gradient of the potential 'slope' upon which the ions find themselves when the release potential is applied.

In an idealized storage device or ion trap, the ions are all in the same place and leave with exactly the same energy when ejected. This means that they arrive at the same time at any chosen location downstream of the ion trap. In reality, of course, the ions have a range of kinetic energies and start off from different locations within the trap. Hence the ions of the same m/z arrive at different times downstream of the ion trap. The purpose of TOF focussing is therefore to cause ions further back in the trap to 'catch up' with ions ejected from the front of the trap, by ensuring that the ions nearer the front of the trap move more slowly than those leaving later. The release potential is chosen so that the ions are ejected without being affected significantly by the random perturbations of thermal energy spread. Although it is necessary that the potential drop is at least as much as the average kinetic energy, a multiple of two is preferred, of five is more preferable, and at least one order of magnitude is most preferable.

This second condition provides the further advantage that the ions will be relatively energetic upon arrival at or adjacent the electrostatic trap. Electrostatic traps have an energy acceptance window, which is centred at a relatively high energy, so that the ions ejected in accordance with the conditions of the present invention are within that energy acceptance window.

Provided that the foregoing conditions are met, the ions will arrive at the electrostatic trap as a convolution of short, energetic packets of similar m/z. Such packets are ideally suited to an electrostatic trap (and particularly the preferred embodiment of an orbitrap) because the FWHM of each ion packet's TOF distribution for a given m/z ratio is then less than the period of oscillation of those sample ions having that m/z when in the electrostatic trap. In other words, the packets are sufficiently coherent for detection to take place.

In preferred embodiments, the ions are pre-cooled, for example in the storage device. This reduces the thermal energy of the ions and also their energy spread, hence reducing the ratio of kinetic energy to release voltage which is the second prerequisite set out above. Pre-cooling may be achieved by collisional cooling, for example. Furthermore, the trapping voltage may be applied so as to force the ions in the storage device towards the exit thereof. This may either be carried out throughout the trapping period or may, in preference, be carried out only immediately prior to ejection.

To obtain bunching of the sample ions at the electrostatic trap, it is preferable to employ an axially segmented linear trap (LT) as the storage device. A differential, preferably DC, voltage is applied between the two or more segments of the LT so as to force the ion cloud within the LT towards the exit thereof. This procedure may be carried out after trapping and cooling of the sample ions received from an ion source in the storage device, which may be achieved by applying voltages to the pole segments so as to create an axial potential well whose base is in the middle of the LT. Alternatively, the bottom of the potential well may be located from the outset at or towards the exit from the storage device. It is particularly preferable that the bottom of the potential well is no more than twice the diameter inscribed by the poles of the storage device away from the storage device exit.

The ions in the storage device are preferably gated out of the exit thereof by applying one or more voltage pulses, to an end electrode of the storage device for example.

The condition for correct focussing or bunching of the sample ions at or adjacent the electrostatic trap is met, in preferred embodiments, by the requirement that the period of oscillation of those ions when injected into the electrostatic trap is shorter, and preferably much shorter, than the time of flight of those sample ions between the storage device exit and arrival at the electrostatic trap entrance.

In alternative embodiments, the further condition that the FWHM time of flight distribution of the ions arriving at the electrostatic trap should be less than the TOF along each detection electrode in the electrostatic trap is imposed as well.

In a particularly preferred embodiment, the storage device is arranged to receive ions along a first direction and to release them from the storage device along a second, orthogonal direction. This permits much higher space charge capacity and better ion beam parameters.

In that case, it is preferable that the storage device should be curved along the first direction. This improves geometric focussing. Optionally, lenses may be added to convert a wide angle beam into a narrow beam. The method may also include boosting the ion energies prior to their arrival at the electrostatic trap entrance.

In preferred embodiments, the method is employed for the generation, storage and detection of sample ions in MS-only mode. Alternatively, the method may be employed for collision-induced dissociation of the ions to produce daughter sample ion fragments. In either case, it is preferable to select the release voltage so as to focus the ions on the entrance to the orbitrap. In an alternative embodiment, however, the method may be employed to detect fragment ions using surface-induced dissociation. In this case, the method preferably further comprises focussing the sample ions through the electrostatic trap and onto a collision surface. The fragment ions which result are then accelerated back towards the electrostatic trap.

It is particularly preferable that the ions arrive at the electrostatic trap at an angle tangential to a central plane of the electrostatic trap. This is preferably achieved by lenses between the ion trap and the electrostatic trap. The benefit of this is that no further excitation of the ions is necessary once they enter the electrostatic trap. This in turn reduces the amount of electronics necessary for correct operation of the electrostatic trap, and is to be compared with the arrangement of U.S. Pat. No. 5,886,346 referenced above.

The lenses between the ion trap and electrostatic trap, where present, preferably offer no direct line of sight between the inside of the ion trap and the inside of the electrostatic trap. This arrangement prevents streaming of ions and gas carryover from the (relatively high pressure) ion trap into the (relatively lower pressure) electrostatic trap.

Detection of the sample ions in the electrostatic trap may be achieved in a number of ways. Most preferably, the electrostatic trap is of the orbitrap type and ions are trapped in a hyper-logarithmic field. As bunches of coherent ions of different m/z pass by the outer electrodes of the orbitrap, an image current is induced therein. This current may be amplified and then processed to generate a TOF spectrum, for example by Fourier transform analysis.

The field within the electrostatic trap may preferably be compensated by applying a compensating voltage (which may be time dependent) to a field compensator during detection of the ions. This procedure ensures minimum field perturbation within the volume occupied by the ion trajectories. Additionally or alternatively, during ion injection into the electrostatic trap, the field compensator may be arranged to act as a deflector to improve the trapping efficiency of the electrostatic trip.

As with previous ion traps, and LTs in particular, the ion trap may contain facilities for resonance or mass-selective instability scans to provide for data-dependent excitation, fragmentation or elimination of certain m/z ratios.

The optimum duration of ion trapping in the ion trap may be determined prior to commencement of mass analysis by carrying out a pre-scan. Preferably, a secondary electron multiplier (SEM) or the like is employed. The SEM may be located radially of the ion trap and in that case mass-selective instability or a resonance excitation scan in the ion trap may be used. Most preferably, however, an axial SEM is employed downstream of the electrostatic trap and on an ion beam axis. In this case, ions are preferably injected into the electrostatic trap just as they would be for subsequent mass analysis.

According to a second aspect of the present invention, there is provided a mass spectrometer comprising: (a) an ion source arranged to supply a plurality of sample ions to be analysed, each of which has a mass-to-charge ratio m/z; (b) an ion storage device comprising a plurality of storage device poles and having a storage device entrance end through which the said sample ions are received and a storage device exit end through which the said sample ions may exit; (c) a voltage source arranged to supply a trapping voltage to the storage device poles so as to contain at least a proportion of the sample ions received through the storage device entrance end of the storage device within a volume ρ of the storage device in a trapping mode during at least a part of a trapping period, the thus trapped ions each having a kinetic energy E_k such that there is an average kinetic energy $\overline{E}_k$ of the ions in the volume ρ during the trapping period or the said part thereof, and to supply a release voltage to the storage device in an ion ejection mode so as to controllably release at least some of the said sample ions contained within the said volume ρ of the storage device through the storage device exit end, the release voltage being of a magnitude such that the potential difference then experienced by the ions across the volume ρ is greater than the said average kinetic energy $\overline{E}_k$ during the trapping period or said part thereof, and further wherein the release voltage is such that the electric field generated thereby at any first point across the volume ρ, upon application of the said release voltage, is no more than 50% greater or smaller than the electric field generated thereby at any other second point across the volume ρ; and (d) an electrostatic trap having an electrostatic trap entrance arranged to receive those ions released through the storage device exit end and meeting the criteria imposed by the applied trapping and release potentials, as a convolution of bunched time of flight distributions for each m/z, each distribution having a full width at half maximum (FWHM); the electrostatic trap further comprising a plurality of electrodes arranged to trap ions received through the electrostatic trap entrance therebetween so that the said trapped ions describe movement having periodic oscillations in at least one direction.

As with the method of the first aspect, a segmented multipolar ion trap is preferable. In that case, to maximise focussing or bunching of ion packets at the entrance to the electrostatic trap, the length of the segment of the pole pieces proximal the ion trap is preferably shorter than twice the inscribed diameter between the segments of the ion trap (measured radially), and most preferably shorter than the inscribed diameter. Also, the distance between the ion trap exit and the centre of the segment closest thereto is preferably greater than or equal to the said inscribed diameter.

Other features and advantages of the invention will become apparent with reference to the appended claims and to the following specific description.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention may be put into practice in a number of ways, and some specific embodiments will now be described by way of example only and with reference to the accompanying drawings in which:

FIG. **1** is a schematic side view of a mass spectrometer embodying the present invention and including an ion trap and electrostatic trap;

FIG. **2** shows schematically and in perspective a part of the ion trap of FIG. **1**;

FIG. **3** shows a front view of the electrostatic trap of FIG. **1**;

FIG. **4***a* shows, schematically, the potential distribution in the ion trap of FIGS. **1**, **2** and **3** when ions are trapped therein;

FIG. **4***b* shows, schematically, the potential distribution in the ion trap of FIGS. **1**, **2** and **3** at the point when trapped ions are ejected from the ion trap;

FIG. **5** shows a front view of an alternative electrostatic trap for use in the mass spectrometer of FIG. **1**;

FIG. **6** shows an alternative configuration of the mass spectrometer of FIG. **1**, again in schematic side view and including a curved ion trap along with an electrostatic trap;

FIG. **7** shows a sectional view through the curved ion trap of FIG. **6**; and

FIG. **8** shows a side view of an electrostatic trap for use with the mass spectrometer of FIG. **1** OR FIG. **6**, in combination with a collision surface downstream of the electrostatic trap to allow operation of the mass spectrometer in surface-induced dissociation mode.

Referring first to FIG. **1**, a mass spectrometer **10** is shown. The mass spectrometer comprises a continuous or pulsed ion source **12**, such as an electron impact source, an electrospray source (with or without a collisional RF multipole), a matrix-assisted laser desorption and ionisation (MALDI) source, again with or without a collisional RF multipole, and so forth. In FIG. **1**, an electrospray ion source **12** is shown.

The nebulized ions from the ion source **12** enter an ion source block **16** having an entrance cone **14** and an exit cone **18**. As is described, for example, in WO 98/49710, the exit cone **18** has an entrance at 90° to the ion flow in the block **16** so that it acts as a skimmer to prevent streaming of ions into the subsequent mass analysis components.

A first component downstream of the exit cone **18** is an ion cooler **20** which reduces the energy of the sample ions from the ion source **12**. Cooled ions exit the ion cooler **20** through an aperture **22** and arrive at a quadrupole mass filter **24** which is supplied with a D.C. voltage upon which is superimposed an arbitrary r.f. signal. This mass filter extracts only those ions within a window of m/z of interest and the chosen ions are then released to a linear ion trap **30**. The ion trap **30** is segmented, in the embodiment of FIG. **1**, into an entrance segment **40** and an exit segment **50**. Although only two segments are shown in FIG. **1**, it will be understood that three or more segments could instead be employed. As better seen in FIG. **2**, the segments **40, 50** are each formed from four rods which are radially spaced so as to form a trapping volume **60** between them.

To trap ions within the trapping volume **60**, a voltage source (not shown) applies an RF voltage to each of the segments **40, 50**. The application of an RF field generates a potential well in the axial direction. Collisions between ions entering the linear trap **30** rapidly cause these ions to sink towards the bottom of the potential well.

The ends of the linear trap **30** are bounded by exit and entrance electrodes **70, 80** respectively. These electrodes are supplied with a DC voltage V_D and V_a respectively. As will be familiar to those skilled in the art, the linear trap **30** may also contain facilities for resonance or mass-selective instability scans, to provide data-dependent excitation, fragmentation or elimination of selected mass-to-charge ratios.

In preference, the length of the exit segments **50** is not in excess of the inscribed diameter D between the rods (FIG. **2**). Also, the distance x between the exit electrode **70** and the axial centre of the exit segment **50** is preferably comparable to, or greater than, the inscribed diameter D (again, see FIG. **2**).

The linear trap **30** may have a pressure gradient therein. In this way, the conditions in one part of the trap **30** are optimised for the best dissipation of energy through ion collisions, whilst near the exit electrode **70**, the conditions may be optimised for the best trapping, lowest fragmentation and so forth. The pressure gradient may, for example, be created through the introduction of additional gas inlets.

Downstream of the exit electrode is a deflection lens arrangement **90** including deflectors **100, 110**. The deflection lens arrangement is arranged to deflect the ions exiting the linear trap **30** in such a way that there is no direct line of sight connecting the interior of the linear trap **30** with the interior of an electrostatic orbitrap **130** downstream of the deflection lens arrangement **90**. This prevents streaming of energetic ions from the relatively high pressure linear trap **30** into the relatively low pressure orbitrap **130**. The deflection lens arrangement **90** also acts as a differential pumping aperture.

Downstream of the deflection lens arrangement **90** is a conductivity restrictor **120**. This sustains a pressure differential between the orbitrap **130** and the lens arrangement **90**.

Ions exiting the deflection lens arrangement **90** through the conductivity restrictor **120** arrive at the orbitrap **130**. The orbitrap **130** has a central electrode **140** as may better be seen with reference now to FIG. **3**. The central electrode **140** is connected to a high voltage amplifier **150**.

The orbitrap **130** also contains an outer electrode split into two outer electrode parts **160, 170**. Each of the two outer electrode parts **160, 170** is connected to a differential amplifier **180**. Preferably, this differential amplifier is maintained at virtual ground.

Referring once more to FIG. **1**, downstream of the orbitrap **130** is a secondary electron multiplier **190**, on the optical axis of the ion beam. Although not shown in FIG. **1**, the secondary electron multiplier (SEM) **190** may also be located on the side of the linear trap **130**.

The system, and particularly the voltages applied to the various parts of the system, is controlled by a data acquisition system. This data acquisition system is in itself known and does not form a part of the present invention. Accordingly, it is not shown in the Figures and will not be described further. The data acquisition system may also carry out signal processing as described below. Likewise, a vacuum envelope is also provided, to allow differential pumping of the system. Again, this is not shown in the Figures, although the typical pressures are indicated in FIG. **1**.

In operation, ions from the ion source **12** enter the segmented linear trap **30** and are reflected by an elevated potential V_D on the exit electrode **70** thereof. AC voltages at RF frequencies are applied to the segments of the trap to provide a quasi-potential well in the radial direction whilst DC voltages V_a, V_b and V_c provide a potential well along the axis of the linear trap **30**. The pressure inside the linear trap **30** is chosen in such a way that ions lose sufficient kinetic energy during their first pass through the trap that they accumulate near the bottom of the axial potential well. Before ions are removed from the linear trap **30**, the DC voltages V_a, V_b, V_d and V_D may be varied in such a way that the centre of ion cloud within the linear trap **30** is shifted into the end section of the linear trap, that is, into the volume defined between the rods in the exit segment **50** adjacent to the exit electrode **70**. As an alternative, the bottom of the axial potential well may instead be located in this exit segment **50** from the start of ion storage in the linear trap **30**.

FIG. **4a** shows, not to scale, the potential electrode **80** and the exit electrode **70** when ions are trapped therein. It will be seen that the ions sit in a potential well defined by the difference in potentials between the exit electrode **70**, the exit segment **50** of the trap **30** and the entrance segment **40** thereof.

At the end of storage, the data acquisition system starts to ramp the voltage applied to the central electrode **140** in the orbitrap **130** and, simultaneously, applies a voltage pulse to the exit electrode **70** of the linear trap **30**. In presently preferred embodiments, a single pulse is applied to empty the linear trap. However, multiple pulses may be employed instead. In any event, the delay between successive pulses is chosen in such a way that all of the mass range of interest arrives into the orbitrap **130** during the correct phase of the voltage applied to the central electrode **140** thereof as it is ramped. Although the ramping of the voltages on the central electrode of the orbitrap **130** and the exit electrode **70** of the linear trap are timed to each other, they do not however need to be synchronous. Thus, the voltage applied to the central electrode **140** of the orbitrap **130** may start to ramp before the pulse is applied to the exit electrode **70** on the linear trap, and may continue to ramp for a period (e.g. tens of microseconds) after the linear trap has been emptied.

FIG. **4***b* shows the potential at the different points along the ion trap **30** between the entrance **80** and the exit electrode **70** again not to scale, when such a pulse is applied to the exit electrode **70**. Because the pulse is negative (in the convention adapted to illustrate the specific embodiment described, the ions previously trapped in the potential well instantaneously find themselves on a "slope" which accelerates them away from the ion trap **30**. As will be explained below, the ejection technique causes the ions leaving the ion trap **30** to be time-of-flight focussed onto the entrance of the electrostatic trap **130**.

It is important, for correct trapping of ions in the orbitrap **130**, that they arrive at the entrance to the orbitrap when the voltage on the central electrode **140** thereof is between approximately $(D_1/D_2)^{1/2}$ V, and V, where V is the final, static voltage on the central electrode **140**, D_1 is the outer diameter of the central electrode **140**, and D_2 is the inner diameter of the outer electrode formed from the outer electrode parts **160** and **170**. The ion energy at the entrance to the orbitrap **130** also needs to lie within a certain range.

Whilst the voltage applied to the central electrode **140** of the orbitrap **130** is ramped, ions are directed and focussed by the linear trap **30** and the deflection lens arrangement **90** to the entrance of the orbitrap **130**. The ions enter the field within the orbitrap **130** tangentially to the outer electrodes formed from the outer electrode parts **160**, **170** and are prevented from hitting this electrode again by a monotonically-increasing electric field, which squeezes the ions closer to the centre of the trap. Tangential injection into the orbitrap **130** is achieved by displacing the trap relative to the centre of the beam of ions arriving from the ion trap **30**. By way of example only, the orbitrap **130** may be positioned so that ions enter it at a radius of 17.4 mm with z=10 mm, the highest internal radius of the electrodes being 20 mm in this specific example.

The rise time of the electric field depends on the mass range to be trapped, ion parameters, and the orbitrap **130**, but is usually between 20 and 200 microseconds. Squeezing stops when there is no more threat of losing ions onto the electrodes.

The orbitrap **130** is shaped so as to generate a hyper-logarithmic field between the central electrode **140** and the outer electrode formed from the outer electrode parts **160**, **170**. The potential distribution of this hyper-logarithmic field may be described in cylindrical coordinates (r, z) by the following equation:

$$V(r, z) = \frac{k}{2}\left[z^2 - \frac{r^2}{2}\right] + \frac{k}{2}(R_m)^2 \ln\left[\frac{r}{R_m}\right] + C$$

where z=0 is the plane of symmetry of the field, C, k, R_m(>0) are constants, and k>0 for positive ions. Such a field creates a potential well along the z axis direction which causes ion trapping in that potential well provided that the incident energy is not too great for the ion to escape. As the voltage applied to the centre of electrode **140** increases, the field intensity increases and therefore the force on the ions towards the longitudinal axis increases, thus decreasing the radius of spiral of the ions as may be seen from FIGS. **1** and **2**. Thus, the ions are forced to rotate in spirals of smaller radius as the sides of the potential well increase in gradient.

There are three characteristic frequencies of oscillation within the hyper-logarithmic field. The first is the harmonic motion of the ions in the axial direction where they oscillate in the potential well with a frequency independent of energy in this direction. The second characteristic frequency is oscillation in the radial direction since not all of the trajectories will be perfectly circular. The third frequency characteristic of the trapped ions is the frequency of angular rotation.

Further details of the preferred electrode arrangement of the orbitrap **130** may be found in U.S. Pat. No. 5,886,346, referenced above, the contents of which are incorporated by reference in their entirety. It will, however, be noted that, in the present case, the ions enter the field tangentially and do not require a separate injection of radial force which in turn reduces the amount of electronic control of the orbitrap **130** that is necessary.

The ion packets arriving at the entrance to the orbitrap **130** are bunched together due to the time of flight focussing created by the ion ejection technique from the linear trap **130**. The ion packets are sufficiently coherent that coherent axial oscillation within the orbitrap **130** takes place without addition excitation. The required degree of coherency depends on the type of detection.

If all ions of the same mass-to-charge ratio were to have the same initial kinetic energy, begin flight at the same time, and from the same position within the trap, then they would all leave the trap together and travel together to arrive at exactly the same moment at any point downstream of the trap. This idealized situation cannot of course be realized in practice, primarily due to three factors which 'smear' the initial peak from a delta function. Firstly, the starting position of different ions of the same mass-to-charge ratio will be different, secondly, the time at which flight begins, and thirdly the initial kinetic energies of the different ions of the same mass-to-charge ratio will be different.

The present invention addresses the non-ideal nature of the ions in the trap by firstly minimizing the spread of initial kinetic energies and by 'bunching' the ions together at one end of the trap (so that they tend to leave from roughly the same point in the trap) and secondly by focussing the ions during flight so that any temporal, spatial or energetic spread which still remains is reduced. FIG. **4***b* shows why this should be so.

When the exit electrode **70** receives the negative going pulse to eject the ions, those ions of the same m/z, which at the moment of pulsing are closest to the exit electrode **70**, experience a smaller voltage drop than those further away from the exit electrode **70**. As the ions of similar m/z which are closest to the exit aperture have a smaller distance to travel to that exit aperture, they pass through it earlier than the ions 'behind' them but at a lower velocity. In other words, ions further away from the exit aperture **70** on application of the negative pulse take longer to be emptied from the tap but leave it at a higher velocity. In this manner, the ions bunch up downstream of the ion trap **30**. By carefully selecting the ejection parameters, the ions in the ion trap **30** may be focussed onto the entrance of the orbitrap **130**.

In the preferred embodiment shown in FIGS. **1** and **3**, a mass spectrum is generated using image current detection, which technique is again described in U.S. Pat. No. 5,886,346. An interference pattern of frequencies of different mass-to-charge ratios produces an image current on the outer electrode parts **160**, **170**. This current is amplified by the differential amplifier **180** and then processed by the data acquisition system by application of a Fourier transform. For this type of ion detection, coherency of the ion packets is achieved as soon as the duration dT (m/z) of a given ion packet of a specific m/z is smaller than the period of axial oscillations within the orbitrap **130**. This period of axial oscillation may in turn be significantly less than the time of flight between the linear trap **30** and the entrance to the orbitrap **130**. To achieve this level of coherence, time of flight focussing or bunching of the ions as they enter the orbitrap **130** is necessary. It is important to distinguish this bunching from first or second order focussing typical in time of flight (TOF) mass analysers. The time of flight between the linear trap **30** and the orbitrap **130** is normally significantly greater than the period of axial oscillations within the orbit trap **130** because of the differential pumping between the linear trap **30** and the orbitrap **130** which necessarily requires a significant spatial separation between the linear trap and the orbitrap **130**.

The electric field strength and the ion trap dimensions are chosen in such a way that the ions catch up, that is, focus in time of flight, just at the entrance to the EST **130**. For example, for a uniform field, the focal point is located 3.d away from the starting point where d is the length of this uniform field as measured from the starting point to the field boundary. Non-uniform fields have focussing properties but the mathematical relations are very complex. The random energy distributions of the ions trapped in the ion trap **30** adversely affect the quality of the TOF focussing; for example, the pulse width becomes comparable with the total time of flight as soon as the energy spread of the ions becomes comparable with the acceleration voltage. In order to address these problems, therefor, the bunching of the ions is achieved, in practice, through a combination of the following requirements.

Firstly, the relative variation of the electric field strength along the ion cloud within the ion trap **30**, or at least the portion to be injected into the orbitrap **130**, should be smaller than unity, and preferably much smaller than unity (such as 10% or even less). Such uniformity of the field along the beam may be achieved by ion squeezing prior to pulsing of the linear trap **30** which in turn is achieved by moving the base of the potential well in the linear trap **30** towards the exit electrode **70** as described above. Collisional cooling of ions within the linear trap also assists in this squeezing. Secondly, the voltage drop across the ion cloud in the linear trap should at least exceed the average kinetic energy during storage, and preferably exceed it by an order of magnitude or more. Such considerable field strength reduces the time of flight spread caused by the initial energies.

The optimum duration of trapping of ions within the linear trap **30** may be determined using a pre-scan after a short storage duration. The secondary electron multiplier **190** allows detection. Where the SEM **190** is located radially of the linear trap **30**, mass-selective instability or a resonance excitation scan in the linear trap **30** may be used. It is preferable, however, to use an axial SEM **190**, after the orbitrap **130**, so that ions are injected in the same way as for the analysis in the orbitrap **130**. It will be understood by those skilled in the art that any other known way of ion detection could be used instead of SEM **190**, such as a collector with a charge-sensitive amplifier, a photomultiplier, semiconductor detectors and so forth.

During detection of ions in the orbitrap **130**, an appropriate voltage, which may be time-dependent, may be supplied to a field compensator **200** adjacent the entrance to the orbitrap **130**. This field compensator ensures minimum field perturbation within the volume occupied by the ion trajectories. During ion injection, this field compensator **200** acts also as a deflector to improve trapping efficiency within the orbitrap **130**.

Although a preferred embodiment has been described, it will be understood that various modifications are contemplated. For example, although a linear ion trap **30** has been described for storage of the sample ions from the ion source **12**, it is to be understood that a quadrupole ion trap could equally be employed for ion storage, cooling and so forth. Quadrupole ion traps are known as such and one example is shown in EP-A-0,113,207.

Furthermore, a second form of orbitrap **130**, seen in front view in FIG. **5**, may be employed instead of the one shown in FIG. **3**. Here, instead of split outer electrode parts, the outer electrode is not split. Instead, the central electrode **140'** is axially segmented with a centre part **220** connected to a pre-amplifier **210**. In this arrangement, pulses of image current from passing ion packets of different m/z are detected by this central, disc-shaped electrode part **220**, amplified by the pre-amplifier **210**, and then processed to yield a time of flight spectrum. A deconvolution method such as is described by M. May et al, in Analytical Chemistry (1992) vol. 64, pages 1601–1605 could be used, or any other signal reconstruction method. Two or more detection electrodes could also be used. The pre-amplifier could also be a differential pre-amplifier with a second input connected to another detection electrode or simply open-ended to improve common mode rejection. For this type of detection, the best results are achieved when the duration dT (m/z) of each ion packet of a particular m/z is not only smaller than the period of axial oscillations in the orbitrap **130**, but also does not exceed the time of flight along each of the detection electrodes.

Furthermore, a mass selective instability scan, such as is described in the above-referenced U.S. Pat. No. 5,886,346 could also be used. In this case, ion injection could be performed also along the central plane of the trap.

FIG. **6** shows another mass spectrometer **10'** which embodies the present invention and currently represents the preferred implementation. Features common to FIGS. **1** and **6** are labelled with like reference numerals.

As with the arrangement of FIG. **1**, the mass spectrometer **10'** comprises an electrospray ion source **12** which provides nebulized ions into an ion source block **16** through an entrance cone **14**. The ions exit the block **16** via an exit cone **18** and pass into an ion cooler **20** at around 10^{-2} mbar. The ions then arrive in a quadrupole mass filter **24** via an aperture **22**, and a range of m/z of the incident ions is selected as described previously.

Ions exiting the mass filter **24** enter an ion trap **300** in a first direction generally parallel with a 'y' axis (see FIG. **6**). The ions are however ejected from the ion trap **300** in a second direction generally orthogonal to their entrance direction, that is, in an 'x' direction as indicated in FIG. **6**. As previously, the ions are focussed in time of flight downstream of the linear trap. Orthogonal ejection of trapped ions additionally allows a much higher space charge capacity than is provided by the arrangement of FIG. **1**, and also provides better ion beam parameters.

Although, to achieve orthogonal ejection, a quadrupole assembly such as is shown in FIG. **1** could be used, this requires the RF voltages applied thereto to be switched off instantaneously. This requires very complex associated electronics, however, so, in preference, the ion trap **300** is elongate in the 'y' direction but is curved in the x-y plane (such that the longitudinal axis is likewise curved in the x-y plane). Curvature of the ion trap **300** improves geometrical focussing. By way of distinguishing from the truly linear trap **130** of FIG. **1**, the ion trap **300** will henceforth be termed a 'curved trap'.

The curved trap **300** includes lenses **310** extending from the exit of the trap which together convert the wide angle incident beam into a narrow beam.

The narrow ion beam exiting the curved trap **300** passes through a beam deflector **320** and into an electrostatic trap **130**. The beam deflector may take one of a variety of forms. A plate in front of the focal point of the focussing lenses could be used to block both ions and gas along the line of sight towards the entrance to the electrostatic trap **130** (for example, around ±5° of arc). Gas arriving from larger angles will not be along the line of sight whereas corresponding ions can be diverted into the electrostatic trap entrance by lenses. The problem with this approach is that it requires the blocking plate to be located in a field-free region which can be difficult to arrange. As an alternative, a toroidal deflector can be employed to achieve the required beam deflection although this introduces extra complexity.

The preferred beam deflector **320** is shown in FIG. **6** and contains a right-angled bend which prevents gas carryover along the line of sight between the curved trap **300** and the electrostatic trap **130**. An 'S'-shaped beam deflector could of course be employed instead (as is shown in FIG. **1**). If the electrostatic trap is arranged with its entrance parallel to the direction of exit of ions from the curved trap **300**. As with the arrangement of FIG. **1**, the ions are usually focussed in time of flight onto the electrostatic trap entrance which then detects in the manner described previously. However, a different focal point can be chosen, as for example when operating in surface-induced dissociation mode (see FIG. **8** below).

Referring now to FIG. **7**, a sectional view of the curved trap **300** of FIG. **6** is shown. The curved trap **300** is preferably RF only and comprises an outer electrode plate **330**, at a D.C. voltage preferably near ground, along with an inner electrode plate **340** at the same D.C. voltage. Sandwiched between the inner and outer electrode plates **330**, **340** are upper and lower centre plate pairs **360***a,* **360***b,* to which is applied an RF voltage having a phase indicated on the drawings as RF−. The upper and lower centre plate pairs **360***a,* **360***b* in turn sandwich an axis plate pair **350** to which is applied an RF voltage (labelled RF+ in FIG. **7**) which is in antiphase to the voltage applied to the upper and lower centre plate pairs **360***a,* **360***b.*

The geometry of the curved trap **300** is chosen in such a way that the minimum of the effective potential (that is, the minimum of the RF field) is located exactly in the middle of the trap. This is the axis of symmetry in the plane XZ and is labelled point Q in FIG. **7**.

The electrodes **330**, **340**, **350**, **360***a* and **360***b* are curved in the XY plane. A DC offset, which is the same as that applied to the inner and outer electrode plates **330**, **340**, is applied to the upper, lower and axis plates. This causes all masses to be stored in the curved trap **300** and cooled in collisions with gas at 0.1–1 mtorr. At the end of the storage, a positive pulse is applied to the outer electrode plate **330**, and a negative pulse of the same amplitude is applied to the inner electrode plate **340** (for positive ions). Ions are extracted by the resulting electric field through a trap exit **370**. The RF voltages do not need to be removed as they have little effect on the beam parameters due to their symmetry. In addition, the RF field strength near the X axis is relatively weak. However, it is preferable to time the pulses applied to the inner and outer electrode plates **330**, **340** so that they are applied in synchronism with the phase of the RF voltages applied to the upper, lower and axis plates **350**, **360***a,* **360***b.*

After sufficient ions have been stored in the trap, they are ejected towards the centre of curvature of the curved trap **300** (see below), and also focussed, both geometrically and in time-of-flight, into a narrow beam that is then introduced into the electrostatic trap **130**.

Still referring to FIG. **7**, a liner **380** may be provided between the trap exit **370** and the lenses **310**. The liner **380** is located in a substantially field-free region of the curved trap. Another pulse, equal to the required ion energy on the entrance to the electrostatic trap **130**, may be applied to the liner **380** at the same time as the pulses are applied to the inner and outer electrode plates **330**, **340**. The pulse is applied to the liner so as to create an "energy lift", that is, to produce a high ion energy in conditions where both the DC offset applied to the curved trap **300** and the potential applied to the outer electrode parts **160**, **170** of the orbitrap **130** (FIG. **3**) are maintained near ground voltage. If the curved trap **300** floats at the acceleration voltage then no energy lift will be required. Nevertheless, it is important that any ion source should have the capability to float as well.

The length of the liner **380** is defined by the required relative mass range: the ratio of the maximum to minimum masses is given by $m_{max}/m_{min}=(L_1/L_2)^2$, where L_1 is the effective distance from the axis to the exit from liner and L_2 is the effective distance to the entrance to the liner. The duration of the pulse applied to the liner **380** is determined by calculating the time-of-flight, to the liner exit, for the lightest mass of interest, so that this mass emerges from the liner **380** at its full energy whilst the voltage on the liner **380** is already back to its normal value (near ground). The duration of the pulses applied to the inner and outer electrode plates **330**, **340** should be longer than this.

It is to be understood that the liner **380** in the curved trap **300** of FIGS. **6** and **7** is equally suitable for the linear trap **30** of FIG. **1**.

The foregoing description of some preferred embodiments has also explained the principles involved with reference to sample ions that are derived directly from an atmospheric pressure ionization source or the like, and are simply stored as such in the ion trap. However, structural analysis of sample ions may also be carried out using TOF focussing and any of the ms/ms modes available. Three modes in particular are contemplated.

In collision-induced dissociation (CID), precursor ions may be selected either by the quadrupole mass filter **24** (FIG. **1**) or inside the ion trap **30**. Ejection of unwanted ions in each of these cases may be performed, for example, by resonant excitation between the opposite rods of each device or by a mass selective instability scan (see, for example, the above-referenced U.S. Pat. No. 5,886,346). This may be achieved by DC biassing one set of rods relative to the other, for example. Fragmentation may be caused by collisions with collision gas at an elevated pressure in a dedicated RF-only multipole or, preferably, in the linear ion trap **30**. The resulting fragments are stored and collisionally cooled in the ion trap **30** and then injected into the orbitrap **130** in the same way as described previously. CID in collisional multipoles is a technique which is well known as such to those skilled in the art and the technique of selecting only the required m/z is likewise a known part of tandem mass spectrometry. Further description of these techniques may be found in "Protein Sequencing and Identification Using Tandem Mass Spectrometry", by M. Kinter, N. E. Sherman, John Wiley and Sons, 2000, and in "Mass Spectrometry/Mass Spectrometry: Techniques and Applications of Tandem Mass Spectrometry", by K. L. Busch, G. L. Glish, and S. A. McLuckey, John Wiley and Sons, 1989.

In surface-induced dissociation (SID), precursor ion selection is typically carried out in the same way as in CID. Precursor ions are stored in the linear trap **30** and then pulsed towards the orbitrap **130**. However, in this case the TOF focus is shifted behind the plane of the entrance of the orbitrap **130**, to a separate plane where a collision surface is located. This is shown schematically in FIG. **8**, which illustrates in side view the orbitrap **130** along with the electrode **140**, the compensator **200** and the secondary electron multiplier **190**. The collision surface **250** is located downstream of the secondary electron multiplier **190** and may be formed from a metal or may instead be metal- or polymer-coated. A fluorocarbon or hydrocarbon self-assembled monolayer plate such as is disclosed in Science, Vol. 275, pages 1447–1450, by S. A. Miller, H. Luo, S. J. Pachuta and R. G. Cooks, (1997) could for example be used.

In this case, precursor ions pass tangentially through the orbitrap **130**, which has electric fields that are low enough to prevent ion losses, and out past the compensator **200** which in this part of the process is switched off to allow passage of the precursor ions. These precursor ions then decelerate in front of the collision surface **250** in a deceleration gap created by a grid **255** and collide with the collision surface **250** at a collision energy determined by a voltage difference between the collision surface and the offset applied to the exit segment **50** of the linear trap. Collision results in the formation of fragment ions at low energies (several electronvolts) which are accelerated by the same electric field towards the orbitrap **130**. Due to the TOF focussing of these precursor ions and the instantaneous nature of SID, fragment ions separate (at least partially) on their way to the orbitrap **130** according to their mass/charge ratio and ions of each mass/charge ratio enter the orbitrap **130** as a short packet. The compensator **200** is switched on during this part of the process so that the fragment ions are then captured by the orbitrap. This allows ions to be captured in the same way as in the MS-only mode described in connection with FIGS. **1** to **5** above. If low resolution of parent selection is sufficient for a given application, then an ion gate (not shown) may be installed between the orbitrap **130** and the collision surface **250** to provide an alternative way of selecting precursor ions. It is in fact possible to use the deflection electrode **200** of the orbitrap **130** as an ion gate.

Finally, metastable dissociation (MSD) mode may be employed with the arrangement and principles outlined previously. Precursor ions may either be selected as described above in connection with the CID and SID modes, or may instead be injected into the orbitrap **130** without prior selection. The only difference from the MS-only mode described in connection with FIGS. **1** to **5** is the activation of ions in the ion trap **30**. Activation may be achieved by pulsed ion extraction in the presence of gas at an elevated pressure (either static or pulsed), wherein the increase of ion internal energy is controlled by the gas pressure, by pulsed electromagnetic radiation (e.g. infrared radiation which can be used to excite ions inside the ion trap **30**, or by resonant or broadband dipolar excitation using at least two pairs of quadrupole rod electrodes in the ion trap **30**. In that case, the increase of internal energy is controlled by the amplitude of the excitation signal and the gas pressure.

Although pulsed ion extraction with a high pressure gas is preferable due to its simplicity, each of the foregoing results in the excitation ("heating") of ions and the consequent formation of metastable ions with a controllable decay constant. The magnitude of the decay constant can be controlled by variation of the intensity of excitation. Before fragmentation becomes noticeable, ions may be injected into the orbitrap **130** and precursor ion selection may even be achieved. On the other hand, excessively long decay times lead to a decrease in the speed of analysis. Therefore, optimum decay times range from several milliseconds to tens of milliseconds.

Precursor ion selection is achieved by applying a radio frequency voltage in resonance with the axial oscillation of precursor ions at a correct phase. A waveform generator (not shown), under the control of the data processing system referred to in connection with FIG. **1**, supplies this RF voltage either to the central electrode **140** (parametric resonance de-excitation at doubled ion frequency, set out in Analytical Chemistry Volume 72, No. 6, p. 1156–1162, by Makarov, and in the above-referenced U.S. Pat. No. 5,886,346), or between the two outer electrode parts **160**, **170** (resonance de-excitation at ion frequency) of the orbitrap **130**. Application of an RF voltage decreases the amplitude of axial oscillation of ions so that only precursor ions are brought into the plane of symmetry of the orbitrap **130**. Precursor ions are left in this state long enough to allow metastable decay to occur. The remaining precursor ions are then excited, together with their fragment ions, by a broadband excitation. Typically, a radio frequency voltage is applied to the two outer electrode parts **160**, **170** by the waveform generator. Coherent oscillations of ions of each mass/charge ratio are detected by detecting an image detection current via the differential amplifier **180** in the same way as described for MS-only mode. Metastable decay of ions other than precursor ions also results in the formation of fragment ions. However, these are uniformly spaced along the orbitrap **130** and thus do not move coherently. No image current is produced for detection in that case. Alternatively, unwanted precursor or fragment ions may be removed by an additional broadband excitation.

What is claimed is:

1. A method of injection of sample ions into an electrostatic trap, comprising the steps of:

(a) generating a plurality of sample ions to be analysed, each of which has a mass-to-charge ratio m/z;

(b) receiving the sample ions through a storage device entrance in an ion storage device having a plurality of storage device poles;

(c) supplying a trapping voltage to the storage device so as to trap at least a proportion of the received sample ions within a volume ρ in the storage device, during at least a part of a trapping period, the thus trapped ions each having a kinetic energy E_k such that there is an average kinetic energy $\overline{E}_k$ of the ions in the volume ρ during the trapping period or the said part thereof;

(d) supplying a release voltage to the storage device so as to controllably release at least some of the said sample ions contained within the said volume of the storage device from a storage device exit, the release voltage being of a magnitude such that the potential difference then experienced by the ions across the volume ρ is greater than the said average kinetic energy $\overline{E}_k$ during the trapping period or said part thereof, and further wherein the release voltage is such that the strength of the electric field generated thereby at any first point across the volume ρ, upon application of the said release voltage, is no more than 50% greater or smaller than the strength of the electric field generated thereby at any other second point across the volume ρ;

(e) receiving those sample ions released from the storage device exit according to the criteria of step (d) through an entrance of an electrostatic trap having a plurality of trapping electrodes, the ions arriving as a convolution of bunched time of flight distributions for each m/z, each distribution having a full width at half maximum (FWHM); and

(f) trapping the received sample ions within the electrostatic trap by applying a potential to the electrodes such that the sample ions describe movement having periodic oscillations in at least one direction.

2. The method of claim **1**, in which the potential applied to the electrodes of the electrostatic trap is ramped towards the trapping voltage at the same time as the release voltage is applied to the storage device to cause the said controllable release of the sample ions therefrom.

3. The method of claim **2**, in which the potential applied to the electrodes of the electrostatic trap commences ramping towards the trapping voltage prior to application of the said release voltage, and continues to be applied until after the release voltage stops being applied.

4. The method of claim **1**, in which the trapping voltage includes an AC component to trap the ions in a radial direction of the storage device.

5. The method of claim **4**, in which the trapping voltage further comprises a DC component, the trapping voltage being selected so as to create a potential well in the storage device defining the said volume ρ, the base of which potential well is adjacent to the storage device exit during at least a part of that trapping period.

6. The method of claim **1**, in which the release voltage includes at least one DC pulse.

7. The method of claim **1**, in which each of the storage device poles is axially segmented into at least two separate pole elements, the step of supplying a trapping voltage to the storage device further comprising supplying a differential DC voltage between at least two separate pole elements so as to cause the sample ions to be trapped in a potential well having a base adjacent to the storage device exit.

8. The method of claim **1**, in which the said period of oscillation of those sample ions in the electrostatic trap is shorter than the said FWHM of the time of flight of those sample ions between ejection from the storage device exit and arrival at the electrostatic trap entrance.

9. The method of claim **1**, in which, during the step (d), the storage device is arranged to release ions stored therein along an axis generally parallel with a major axis of the storage device when said release voltage is applied.

10. The method of claim **9**, in which the storage device is a linear trap whose poles together define an inscribed diameter, and in which the trapping potential is applied so that the base of the potential well is located not more than a distance equal to twice the inscribed diameter from the storage device exit.

11. The method of claim **8**, in which the release voltage is a differential voltage applied across the axial segment adjacent the storage device exit, and wherein the magnitude of the release voltage is greater than the magnitude of the trapping voltage.

12. The method of claim **1**, in which, during the step (d), the storage device is arranged to release ions stored therein along an axis generally orthogonal with a major axis of the storage device when said release voltage is applied.

13. The method of claim **12**, further comprising trapping the ions in a storage device which is curved along its major axis.

14. The method of claim **1**, further comprising applying a voltage to an energy lifter downstream of the storage device, so as to increase the ion energies as they pass through the said energy lifter.

15. The method of claim **1**, further comprising cooling the sample ions to reduce their kinetic energies E_k.

16. The method of claim **15**, in which the cooling is carried out in an ion cooler prior to receipt through the said storage device entrance.

17. The method of claim **15** in which the cooling is carried out within the storage device by forcing sample ions to collide with a collision gas.

18. The method of claim **1**, in which the release voltage is of a magnitude such that the potential difference then experienced by the ions across the volume ρ is at least an order of magnitude greater than the said average kinetic energy E_k.

19. The method of claim **1**, in which the release potential is applied so as to release the ions trapped within the volume ρ such that they focus in time of flight upon the entrance to the electrostatic trap.

20. The method of claim **19**, further comprising directing the ions towards the entrance of the electrostatic trap so that they arrive there at an angle which is tangential to a central plane of the electrostatic trap.

21. The method of claim **1**, in which the release potential is applied so as to release the ions trapped within the volume ρ such that they focus in time of flight upon a collision surface located downstream of the electrostatic trap, the method further comprising accelerating fragment ions, created by the impact of the said sample ions upon the collision surface, back towards the electrostatic trap.

22. The method of claim **1**, further comprising deflecting the sample ions between their exit from the storage device and their entrance to the electrostatic trap such that the said ions do not travel along a line of sight between the storage device exit and the electrostatic trap entrance.

23. The method of claim **1**, further comprising: applying time dependent voltages to the trapping electrodes of the electrostatic trap so as to increase the electric field within the electrostatic trap until the arrival of the FWHM of the highest m/z to be analysed.

24. The method of claim **1**, in which the electrostatic trap is of the orbitrap type having a central electrode and an outer electrode split into two sections, the method further comprising ramping to an electrostatic trapping potential on the said central electrode, and detecting an image current induced by the said trapped ions in the said split outer electrode.

25. The method of claim **24**, in which the ions are confined in the axial direction and constrained to move around the central electrode by a hyper-logarithmic field having a potential distribution of the form: where:

r and z are cylindrical coordinate, z=0 being the plane of symmetry of the field; C, k, Rm(>0) are constants, and k>0 for positive ions.

26. The method of claim **24**, further comprising compensating the field within the orbitrap so as to minimise field perturbation within a volume occupied by the sample ions therein.

27. The method of claim **26**, in which the field is compensated by applying a time dependent voltage to a field compensator in the orbitrap.

28. The method of claim **1**, further comprising determining the optimum duration of trapping within the said storage device.

29. The method of claim **1**, further comprising filtering out a proportion of the sample ions prior to their introduction into the storage device, in accordance with their m/z ratio.

30. A mass spectrometer comprising:

(a) an ion source arranged to supply a plurality of sample ions to be analysed, each of which has a mass-to-charge ratio m/z;

(b) an ion storage device comprising a plurality of storage device poles and having a storage device entrance end through which the said sample ions are received and a storage device exit end through which the said sample ions may exit;

(c) a voltage source arranged to supply a trapping voltage to the storage device poles so as to contain at least a proportion of the sample ions received through the storage device entrance end of the storage device within a volume ρ of the storage device in a trapping mode during at least a part of a trapping period, the thus trapped ions each having a kinetic energy E_k such that there is an average kinetic energy $\overline{E}_k$ of the ions in the volume ρ during the trapping period or the said part thereof, and to supply a release voltage to the storage device in an ion ejection mode so as to controllably release at least some of the said sample ions contained within the said volume ρ of the storage device through the storage device exit end, the release voltage being of a magnitude such that the potential difference then experienced by the ions across the volume ρ is greater than the said average kinetic energy $\overline{E}_k$ during the trapping period or said part thereof, and further wherein the release voltage is such that the electric field generated thereby at any first point across the volume ρ, upon application of the said release voltage, is no more than 50% greater or smaller than the electric field generated thereby at any other second point across the volume ρ; and

(d) an electrostatic trap having an electrostatic trap entrance arranged to receive those ions released through the storage device exit end and meeting the criteria imposed by the applied trapping and release potentials, as a convolution of bunched time of flight distributions for each m/z, each distribution having a full width at half maximum (FWHM); the electrostatic trap further comprising a plurality of electrodes arranged to trap ions received through the electrostatic trap entrance therebetween so that the said trapped ions describe movement having periodic oscillations in at least one direction.

31. The mass spectrometer of claim **30**, in which the storage device poles are each segmented into two or more axially separate segments, the voltage source being arranged to supply a differential DC voltage between a one of the axially separated segments and the other or another of the axially separated segments.

32. The mass spectrometer of claim **31**, in which the segments of the storage device poles are radially spaced from one another to define a trapping volume including the volume of therebetween, the axial length of the segment of each end pole most adjacent to the storage device exit being no greater than twice the inscribed diameter defined by the radial spacing of those end pole segments.

33. The mass spectrometer of claim **32**, in which the storage device further comprises an end cap defining therein a storage device exit, the axial distance between the end cap and a point mid-way along the end pole segments being no less than the said inscribed diameter.

34. The mass spectrometer of claim **30**, further comprising a lens arrangement between the storage device exit and the electrostatic trap entrance, the lens arrangement being arranged to deflect the path of ions between the storage device and electrostatic trap such that they do not travel along a direct line of sight between the interior of the said storage device and the interior of the said electrostatic trap.

35. The mass spectrometer of claim **34**, in which the lens arrangement is arranged to focus the ions into the electrostatic trap at an angle tangential to a central plane thereof.

36. The mass spectrometer of claim **30**, in which the electrostatic trap is an orbitrap comprising a first, central electrode and a second, outer electrode, the second, outer electrode being split into two sections, the mass spectrometer further comprising means for detecting ions constrained within the orbitrap.

37. The mass spectrometer of claim **36**, in which the voltage source is further arranged to supply a potential to the said central electrode, the mass spectrometer further comprising a voltage supply controller which is arranged to control the ramping of the potential on the central electrode in the electrostatic trap so that it occurs over a period of time which encompasses the duration of application of the release voltage to the storage device to cause the said controlled ejection of ions therefrom.

38. The mass spectrometer of claim **37**, in which the voltage supply controller is arranged to apply the said release voltage to the storage device so that the ions arrive at the electrostatic trap whilst the potential on the central electrode is between $(\mathbf{D1}/\mathbf{D2})^{1/2}$ V and V, where V is the final static voltage applied to the central electrode, **D1**, is the outer diameter of that central electrode, and **D2** is the inner diameter thereof.

39. The mass spectrometer of claim **30**, further comprising field compensation means, the voltage supply being further arranged to supply a compensation voltage to the field compensation means so as to minimize field perturbation within the electrostatic trap.

40. The mass spectrometer of claim **30**, further comprising a collision surface located downstream of the electrostatic trap, the ions exiting the storage device being focussed in time of flight onto the said collision surface so as to generate fragment ions for capture by the electrostatic trap.

41. The mass spectrometer of claim **30**, further comprising ion cooling means arranged upstream of the said storage device.

42. The mass spectrometer of claim **30**, further comprising a mass filter arranged upstream of the said storage device.

43. The mass spectrometer of claim **30**, in which the storage device is arranged to receive ions substantially along a first longitudinal axis, and to release the said ions along a second, substantially orthogonal axis.

44. The mass spectrometer of claim **43**, in which the storage device is curved.

45. The mass spectrometer of claim **30**, further comprising an ion deflector downstream of the storage device.

46. The mass spectrometer of claim **30**, further comprising an ion energy booster upstream of the electrostatic trap.

47. A method for injecting sample ions into an electrostatic trap, the method comprising:

supplying a trapping voltage to an ion storage device to trap at least some of a plurality of sample ions within the storage device during at least a part of a trapping period, wherein each sample ion has a mass-to-charge ratio m/z;

supplying a release voltage to the storage device, wherein the release voltage is of a magnitude such that the sample ions released from the storage device arrive at an electrostatic trap as a convolution of bunched time of flight distributions for each m/z;

receiving the sample ions released from the storage device through an entrance of the electrostatic trap, the sample ions arriving as a convolution of bunched time of flight distributions for each m/z, each distribution having a full width at half maximum (FWHM); and

trapping the received sample ions within the electrostatic trap by applying a potential to a plurality of electrodes within the electrostatic trap such that the sample ions describe movement having periodic oscillations in at least one direction.

48. The method of claim **47** wherein supplying a release voltage to the storage device includes ensuring that an electric field experienced by the ions upon leaving the storage device is approximately uniform and ensuring that a potential drop experienced by each ion upon release from the storage device is larger than an average kinetic energy of the ions when trapped in the storage device.

49. A mass spectrometer comprising:

an ion source configured to supply a plurality of sample ions to be analysed, each of which has a mass-to-charge ratio m/z;

an ion storage device comprising a plurality of storage device poles and having a storage device entrance through which the sample ions are received from the ion source and a storage device exit through which the sample ions are released;

a voltage source configured to supply a trapping voltage to the storage device poles so as to contain at least a portion of the sample ions received through the storage device entrance within a volume ρ of the storage device in a trapping mode during at least a part of a trapping period, and to supply a release voltage to the storage device to controllably release at least some of the sample ions contained within the volume ρ through the storage device exit, wherein the release voltage is of a magnitude such that the sample ions released from the storage device arrive as a convolution of bunched time of flight distributions for each m/z at an electrostatic trap; and

the electrostatic trap having an electrostatic trap entrance arranged to receive the ions released through the storage device exit as a convolution of bunched time of flight distributions for each m/z, each distribution having a full width at half maximum (FWHM), the electrostatic trap further comprising a plurality of electrodes arranged to trap ions received through the electrostatic trap entrance therebetween so that the trapped ions describe movement having periodic oscillations in at least one direction.

50. The mass spectrometer of claim **49** wherein the voltage source is configured to supply the release voltage to ensure that an electric field experienced by the ions upon leaving the storage device is approximately uniform and to ensure that a potential drop experienced by each ion upon release from the storage device is larger than an average thermal energy of the ions when trapped in the storage device.

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United States Patent [19]

Makarov

[11] **Patent Number: 5,886,346**

[45] **Date of Patent: Mar. 23, 1999**

[54] **MASS SPECTROMETER**

[75] Inventor: **Alexander Alekseevich Makarov**, Manchester, United Kingdom

[73] Assignee: **HD Technologies Limited**, Manchester, United Kingdom

[21] Appl. No.: **930,568**

[22] PCT Filed: **Mar. 29, 1996**

[86] PCT No.: **PCT/GB96/00740**

§ 371 Date: **Sep. 29, 1997**

§ 102(e) Date: **Sep. 29, 1997**

[87] PCT Pub. No.: **WO96/30930**

PCT Pub. Date: **Oct. 3, 1996**

[30] **Foreign Application Priority Data**

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[51] **Int. Cl.**[6] **H01J 49/42**

[52] **U.S. Cl.** **250/291**; 250/290

[58] **Field of Search** 250/291, 290, 250/292, 293, 295, 281, 282

[56] **References Cited**

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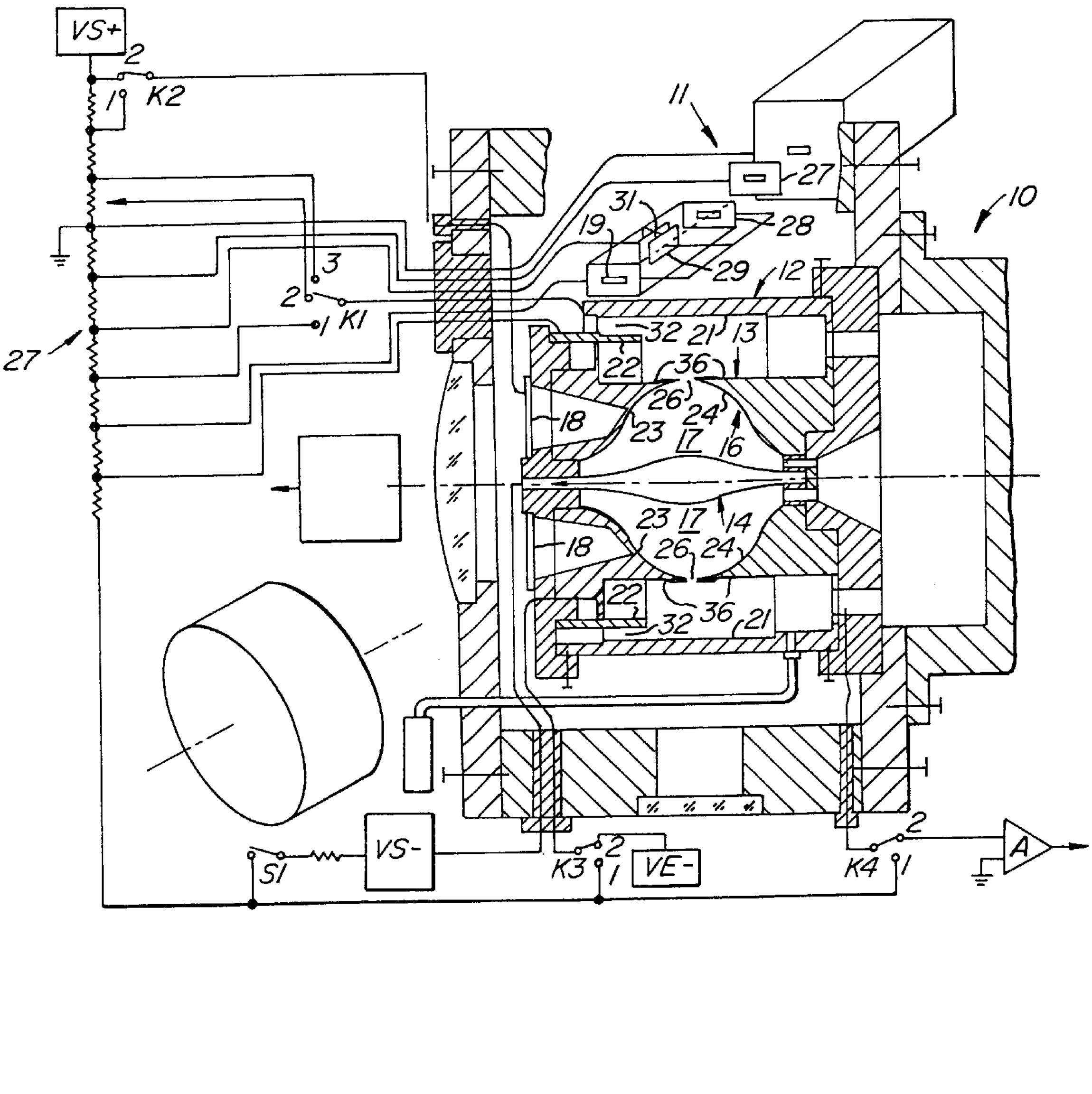
Primary Examiner—Kiet T. Nguyen
Attorney, Agent, or Firm—Townsend and Townsend and Crew

[57] **ABSTRACT**

A mass spectrometer comprises an ion source (**11**), an ion injection arrangement (**12**), field generator defined by shaped electrodes (**14, 16**) and a detector (**18**) to detect ions. The electrodes (**14, 16**) are shaped so as to provide therebetween a field of substantially hyper-logarithmic form whereby ions can be trapped within a potential well of the field for analysis.

22 Claims, 5 Drawing Sheets



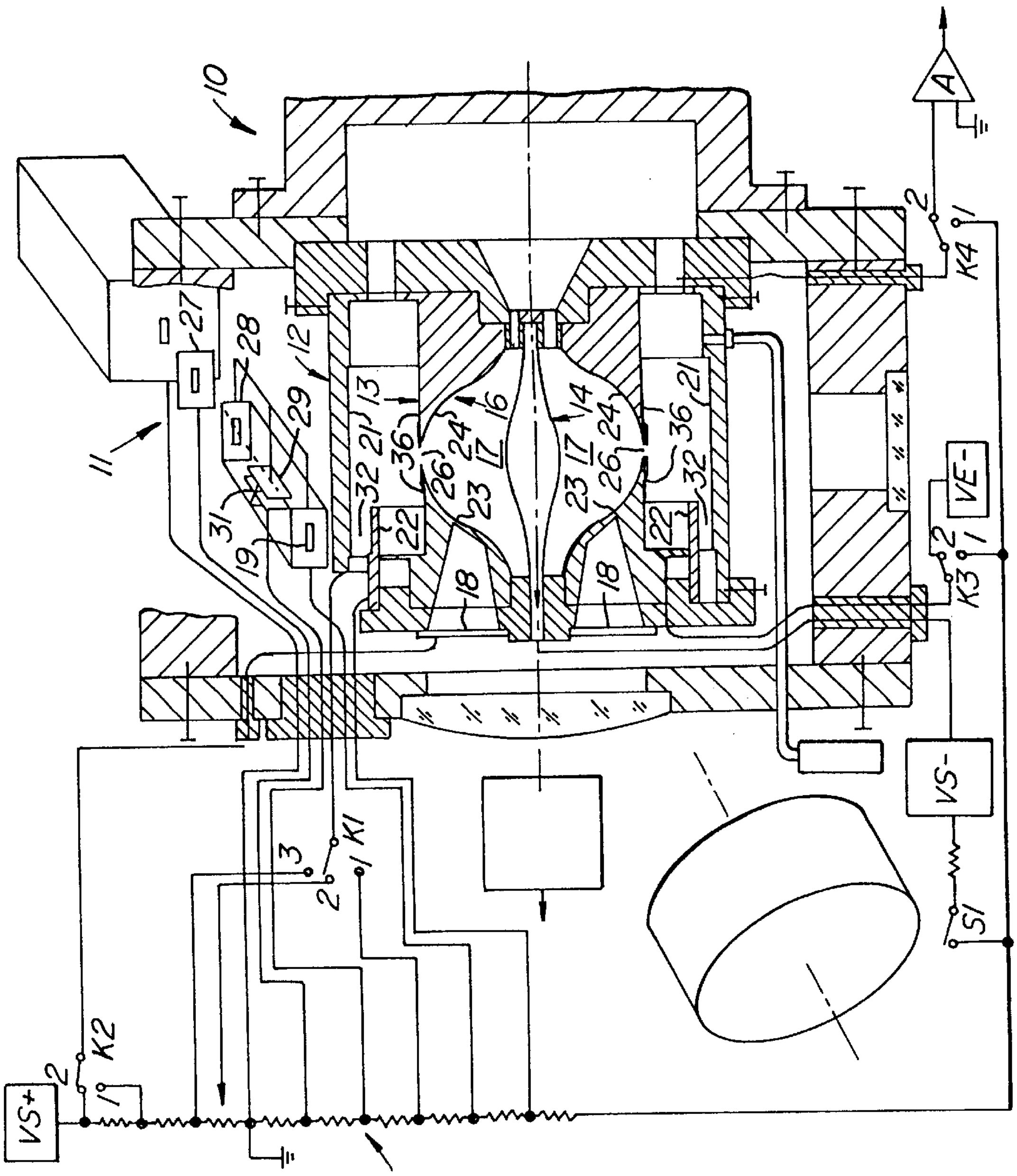


FIG. 1.

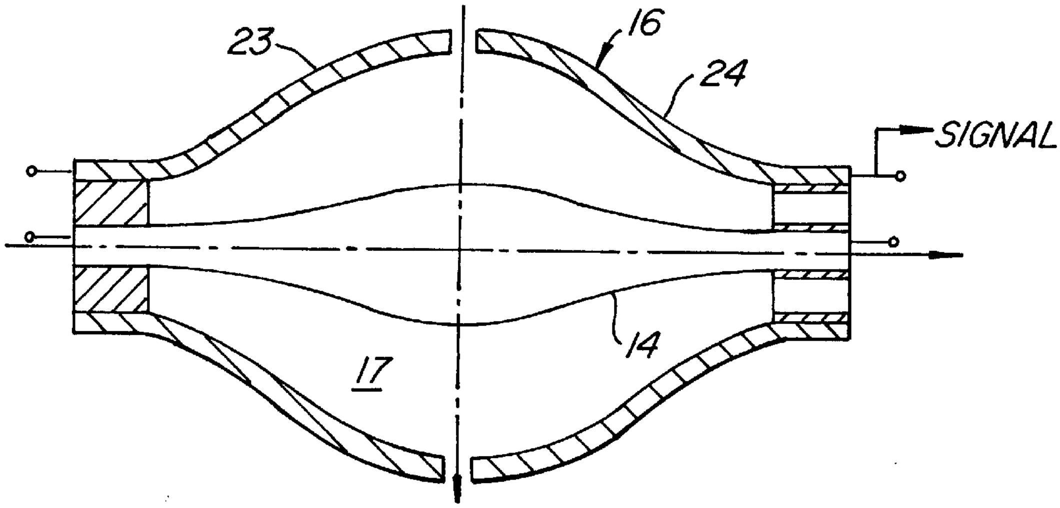


FIG. 2.

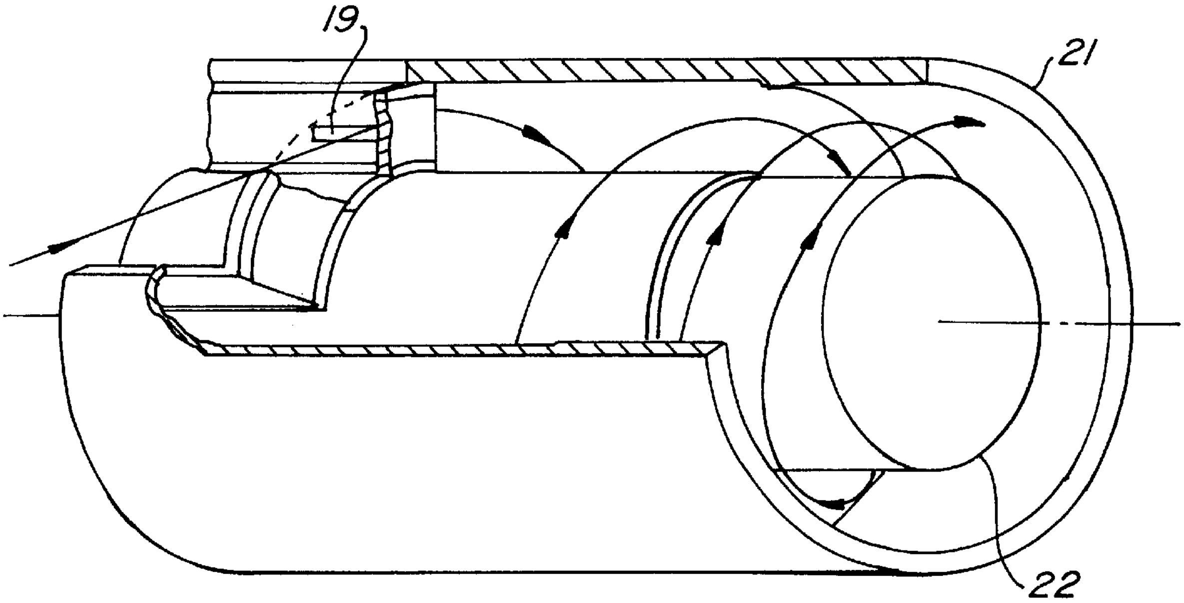


FIG. 3.

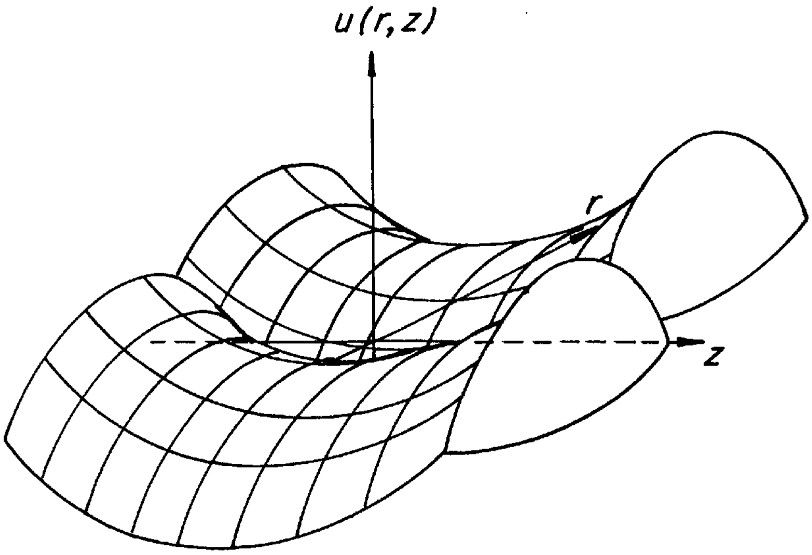


FIG. 4.

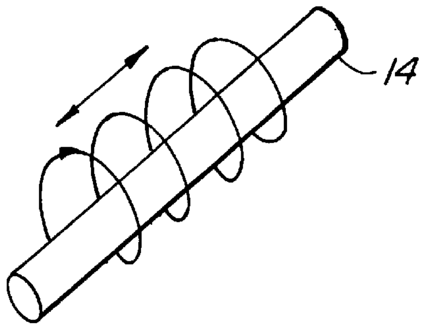


FIG. 5.

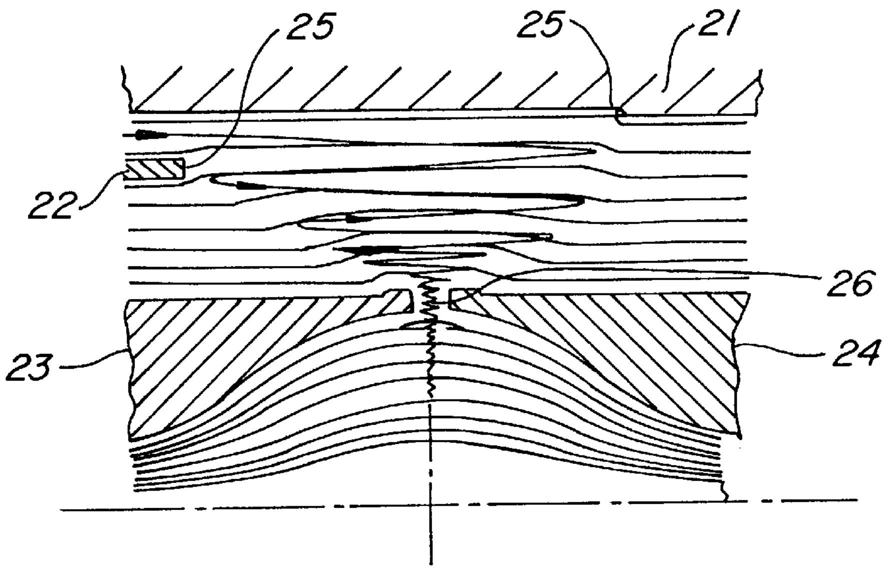


FIG. 6.

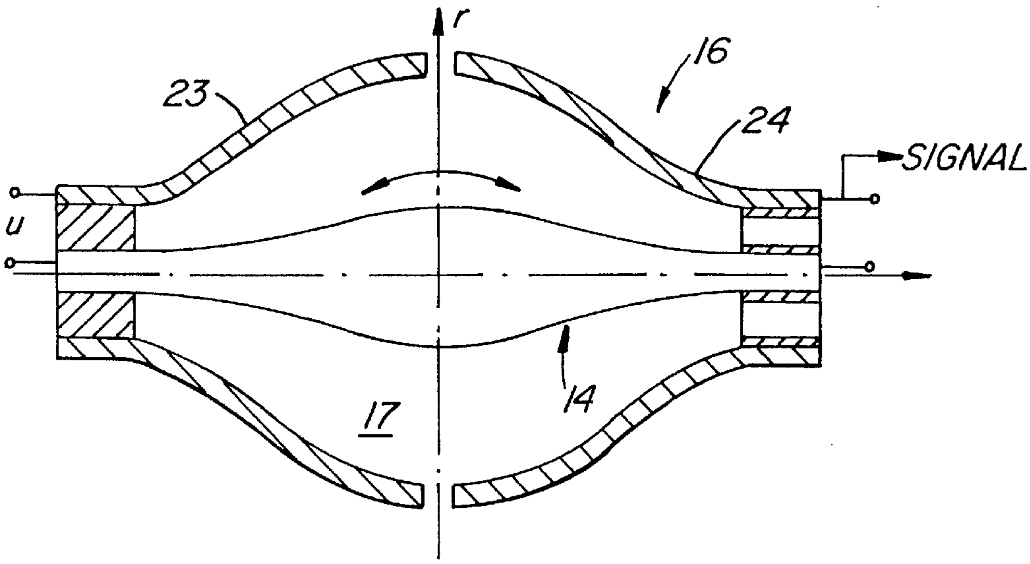


FIG. 7.

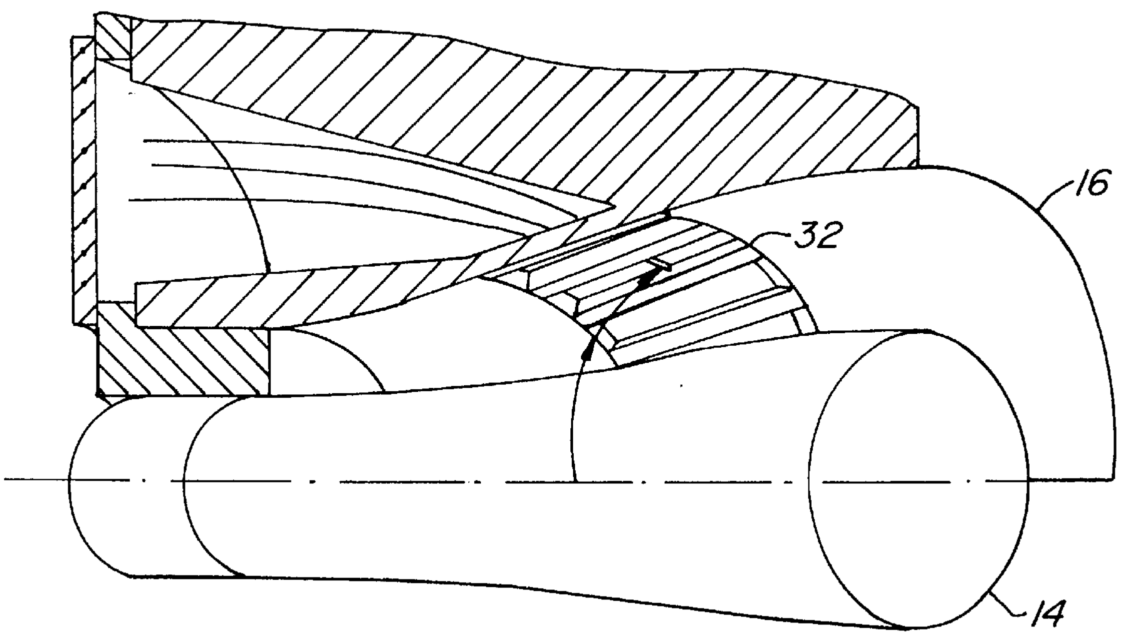


FIG. 8.

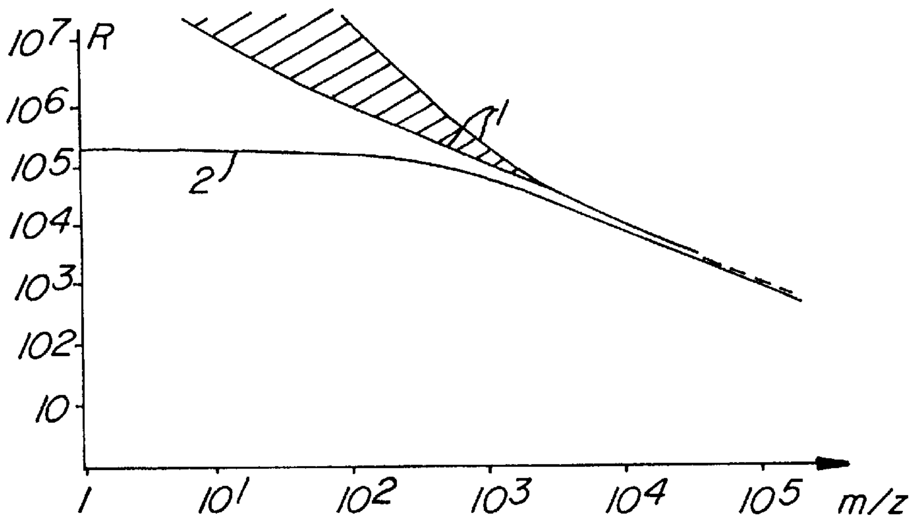


FIG. 9A.

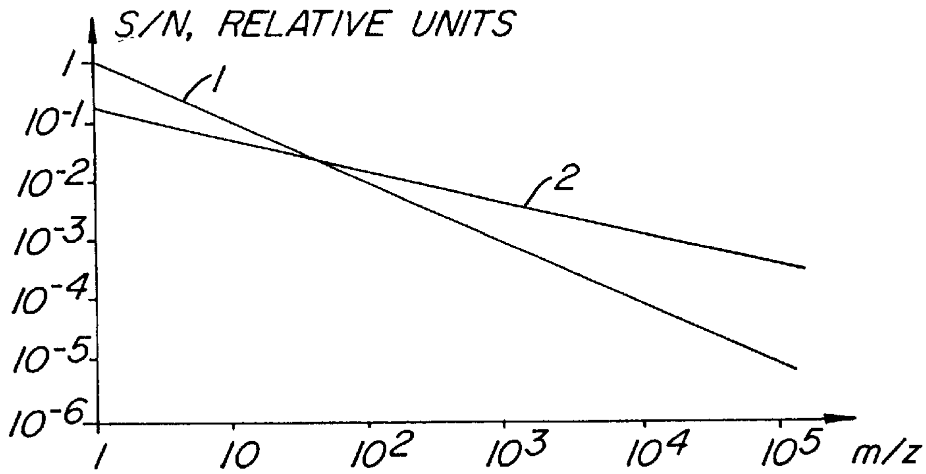


FIG. 9B.

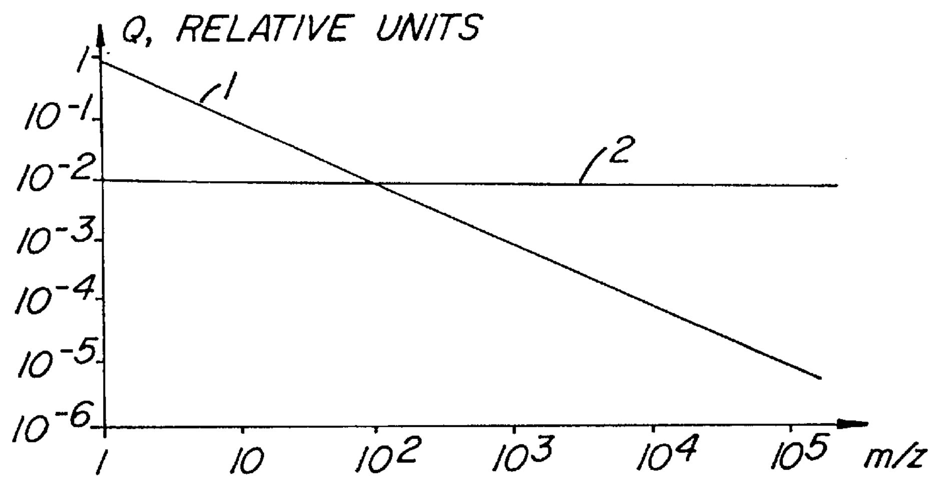


FIG. 9C.

MASS SPECTROMETER

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to improvements in or relating to a mass spectrometer and is more particularly concerned with a form of mass spectrometer which utilizes trapping of the ions to be analyzed.

2. Description of the Prior Art

Molecular or atomic weight of a substance is a useful characteristic which, if detected, can enable the substance to be identified. A mass spectrometer is a measuring instrument which can determine the molecular weight of a substance or other molecule introduced into it for analysis. Mass Spectrometers operate in a number of different ways, however the present invention is concerned particularly with mass spectrometers in which ions are trapped or confined within a particular region of space for analysis purposes. Known types of mass spectrometers of this type are the so-called "quadrupole ion trap" spectrometers and "ion cyclotron resonance" spectrometers.

Quadrupole ion trap mass spectrometers currently available use a three-dimensional quadrupole electric field which oscillates at radio frequencies to trap ions. The ions can then be ejected from the field selectively on the basis of mass/charge ratio enabling the device to operate as a mass spectrometer. This form of spectrometer can be produced relatively inexpensively and relatively small in size, making it a popular choice as a mass selective detector for gas chromatographs (GC-MS).

Ion cyclotron resonance (ICR) mass spectrometers currently available use a combination of an electric field and a very strong magnetic field to trap ions. The trapped ions spiral around the magnetic field lines with a frequency related to the mass of the ion. The ions are then excited such that the radii of their spiralling motion increases and as the radii increase the ions are arranged to pass close to a detector plate in which they induce image currents. The measured signal on these detector plates as a function of time is related to the number and frequencies (hence mass) of the ions. Conventional techniques such as Fourier transformation can be applied to the measured signal to obtain the component frequencies of the ions and hence produce a frequency (and hence mass) spectrum. This type of mass spectrometer is able to produce a very high degree of mass resolution.

However, there-are disadvantages associated with the known forms of mass spectrometer described above. For instance, while the quadrupole ion trap mass spectrometer can be constructed small and cheaply, the mass resolution and mass range obtained is not very high unless the analysis is carried out using very slow scanning. While this is adequate for gas chromatograph mass measurement, it limits the applicability to molecular weight molecules of a biochemical nature. Furthermore, with the ion cyclotron resonance mass spectrometer described above, in order to provide the high magnetic field necessary for the spectrometer to work efficiently, it is necessary to provide a super conducting magnet which in itself is very expensive. Furthermore, a super conducting magnet of the type necessary requires, with technology currently available, the use of liquid helium to cool it and as a continuous supply of this is required, it necessarily results in high running costs of the spectrometer due to the relatively high cost of liquid helium.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved mass spectrometer in which the high mass resolution associated with the ion cyclotron resonance mass spectrometer can be achieved in a small and relatively inexpensive mass spectrometer.

According to the present invention therefore there is provided a mass spectrometer comprising an ion source to produce ions to be analyzed, electric field generation means to produce an electric field within which said ions can be trapped and detection means to detect ions according to their mass/charge ratio wherein said electric field defines a potential well along an axis thereof and said ions are caused to be trapped within said potential well and to perform harmonic oscillations within said well along said axis, said ions having rotational motion in a plane substantially orthogonal to said axis.

Preferably said electric field produced by the electric field generation means is of substantially "hyper-logarithmic form".

With this arrangement it is possible to detect ion mass/charge ratio with a high degree of resolution in a simple and inexpensive manner.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic side view of one form of mass spectrometer according to the present invention;

FIG. **2** is a side view to a larger scale of a part of FIG. **1** showing the field generation arrangement and measurement chamber;

FIG. **3** shows a schematic view of a part of FIG. **1** to a larger scale showing part of one form of ion injection arrangement;

FIG. **4** shows a graphical representation of one form of the potential distribution of the electric field provided by the field generation arrangement;

FIG. **5** shows a diagrammatic representation of the movement of trapped ions in the measuring chamber with the electric field of FIG. **4**;

FIG. **6** shows a diagrammatic representation of the movement of ions from the ion injection arrangement to the measuring chamber;

FIG. **7** shows a side view similar, to FIG. **2** illustrating the movement of the ions in a measurement chamber in the axial direction after excitation;

FIG. **8** shows a diagrammatic representation, partly in section, of one form of ion ejector from the measurement chamber in the MSI mode of operation; and

FIG. **9** shows graphical representations of various parameters of a mass spectrometer indicating the performance of the mass spectrometer of the present invention (**1**) and similar parameters of a conventional ICR mass spectrometer.

DETAILED DESCRIPTION OF A PREFERRED EXEMPLARY EMBODIMENT

Referring now to FIG. **1**, there is shown a schematic representation of a mass spectrometer **10** which comprises an ion source **11**, ion injection arrangement **12**, field generator means **13** defined by the outer and inner shaped electrodes **14**, **16** which define between them a measurement cavity **17** and one or more detectors **18** to detect the ions, either trapped in the field or ejected therefrom in a manner to be hereinafter defined

The ion source **11** comprises either a continuous or pulsed ion-source of conventional type and produces an ion stream which exits through a slit **19** in a front part thereof.

The ion injection arrangement **12** (shown more clearly in FIG. **3**) comprises two concentric cylinder electrodes **21, 22**, the outer electrode **21** being of substantially larger diameter than the inner electrode **22**. The outer cylinder electrode **21** has a tangential hole through which ions from the source pass into the region between the outer and inner electrodes **21, 22**. The injection arrangement **12** is mounted round the field generator means and is in connection therewith in a manner which will be described hereinafter. The outer cylindrical electrode **21** is stepped at ends thereof for a reason which will become hereinafter apparent. While in the embodiment described, the inner cylindrical electrode **22** is formed as a separate electrode, it is possible to use a top surface **36** of the shaped electrode **16** as indicated in FIG. **1** to form entirely the function as inner cylinder electrode **22**.

The field generation arrangement **13** is disposed within the confines of inner cylinder electrode **22** and includes two shaped electrodes, internal and external field generator electrodes **14, 16** respectively. The space **17** between the internal and external shaped electrodes **14, 16** forms the measurement chamber. The electrodes **14, 16** are shaped for a reason which will become hereinafter apparent. The outer shaped electrode **16** is split into two parts **23, 24** by a circumferential gap **26**, an excitation electrode part **23** and a detection electrode part **24**. The circumferential gap **26** between the outer electrode parts **23, 24** allows ions to pass from the injection arrangement to the measurement chamber **17** in a manner to be hereinafter defined.

The cylindrical and shaped electrodes are connected to respective fixed voltage supplies via a potential divider arrangement **27** which allows a desired voltage to be applied to the electrodes.

The measurement chamber **17** is linked to a vacuum pump which operates to evacuate the measurement chamber to a UHV of approximately 10^{-8} Torr or lower.

The internal and external shaped electrodes **14, 16** when supplied with a voltage will produce respective electric fields which will interact to produce within the measurement chamber **17** a so-called "hyper-logarithmic field". The potential distribution of a hyper-logarithmic field, is shown in FIG. **4** and is described in cylindrical coordinates (r,z) by the following equation:

$$u(r,z)=k/2((z-a)^2-r^2/2)+b\ln(r/c)+d$$

where a, b, c, d and k are constants. It can be seen from this figure that such a field has a potential well along the axial (Z) direction which allows an ion to be trapped within such potential well if it has not enough energy to escape. The field is arranged such that the bottom of the potential in the radial direction (i.e. along axis r in FIG. **4**) lies along the longitudinal axis of the measurement chamber **17** shown in FIGS. **1** and **2**. While for the purposes of illustration of the present invention a hyper-logarithmic field will be described, it is thought that other forms of field will be capable of being used, the only restriction on the form of field generated being that the field defines in potential terms a three-dimensional well in which ions can be trapped, and ions are prevented from striking an inner electrode by virtue of rotational motion about this electrode.

A suitable detector which may be connected to a microprocessor based circuit is provided which analyzes the signal in accordance with conventional Fourier analysis techniques by detecting one or more of the following frequency characteristics of the ions in the chamber **17**, i.e. harmonic motion in its axial direction, oscillation in the radial direction and the frequency of angular rotation. The most appropriate frequency to give the required high performance is the harmonic motion in the axial direction. These frequencies can be detected while the ions are in the measurement chamber **17**. The ions may also be detected after they have been ejected from the chamber **17**, as desired or as appropriate. Where detection in the measurement chamber **17** is used, it is possible to use one half of the outer electrode **16** as a detector as will be described hereinafter. Each of the electrodes **14, 16** may be split into two or more electrode segments, if desired.

In use, ions to be measured are produced by the ion source **11**, focused and accelerated by plates **27–31** and leave the ion source **11** through entrance slit **19**.

The ion source **11** is directed towards a tangential inlet aperture (not shown) in the outer cylindrical electrode **21** and the ions enter the injection cavity **32** between the cylindrical electrodes **21, 22** with a small axial velocity component so that the ions move axially away from the inlet. The field produced between the two cylindrical electrodes **21, 22** causes the ions to enter a spiral trajectory around the inner cylindrical electrode **22**.

In order to inject the ions from the injection arrangement **12** into the measurement cavity **17**, it is necessary to modify the electric field produced by the cylinder electrodes **21, 22** (and **36** where appropriate) to define a potential valley which is directed towards the circumferential gap **26** between the excitation and detection electrode parts **23, 24**. In the apparatus of the present invention, this is achieved by providing steps in the cylinder electrode walls **25** which, in combination with the fringing effects caused by the circumferential gap modifies the field in the manner desired. Of course, it may be possible to achieve the same effect using different means as desired or as-appropriate. By increasing the voltage applied to the electrodes **21, 22, 23, 24** with time, the sides of the potential well are increased in gradient thereby forcing the ions to oscillate within the confines of this valley. Furthermore, as the voltage increases, the field intensity increases and therefore the force on the ions towards the longitudinal axis increases thus decreasing the radius of spiral of the ions. Thus it can be seen that the ions converge into the gap **26** by virtue of being forced to rotate in spirals of smaller radius and by a potential well caused by modification of the field produced by the electrodes **21, 22, 23, 24**. This is shown schematically in FIG. **6**. Of course, the injection arrangement **12** can take any form as desired or as appropriate, for example electrodes **21, 22** need not be present and electrodes **23, 24** can be segmented, and a part of the field can be switched off during injection and switched on again to trap the ions once injection has been completed. The present arrangement has been developed to provide greater sensitivity.

After sufficient ions have been directed into the measurement chamber **17**, the voltage supply to spaced electrodes **14, 17** can be maintained constant and the voltage supply to the cylinder electrodes **21, 22** can be changed such that all ions outside the hyper-logarithmic field are lost in the injection arrangement **12**.

The shaped electrodes **14, 16** in the field generation arrangement are shaped so as to have the shape of equipotential surfaces in, the required potential distribution. The hyper-logarithmic field is created in the measurement chamber **17** by the electrodes **14, 16** and the ions injected from the injection arrangement **12** through gap **26** are maintained within the potential well in this field so as not to strike inner electrode **14** by ensuring that they have sufficient rotational energy to orbit the electrode **14** in a spiral trajectory. Thus the ions to be analyzed are trapped in the field and are forced to oscillate back and forth within the confines of the well created by the hyper-logarithmic field in a spiral trajectory around the central electrode **14**.

Once the ions are trapped in the hyper-logarithmic field, various methods of analysis can be used as are described hereinafter.

After mass analysis has been completed, any remaining ions in the injection or measuring chamber are swept away by, changing the voltage supply to the electrodes **14**, **16** for a short time.

Mass analysis can be carried out using the mass spectrometer of the invention in one of two modes which will be considered in turn:

1. Fourier Transform Mode

There are three characteristic frequencies of oscillation within the field. The first is the harmonic motion of the ions in the axial direction where they oscillate in the potential well with a frequency independent of energy in this direction.

The second characteristic frequency is oscillation in the radial direction since not all the trajectories will be perfectly circular.

The third frequency characteristic of the trapped ions is the frequency of angular rotation.

In order to detect the frequencies of oscillations the motion needs to be coherent. The radial and rotational oscillations are not coherent since ions are injected into the measurement cavity **17** continuously over a period of time, and hence the distribution of ions around the inner shaped electrode **14** is random. It is easiest to induce coherence in the axial oscillations and therefore the outer electrode **16** is formed in two parts **23**, **24** as described above for this purpose. If a voltage pulse is applied to one part **23** of this electrode, the ions which exist as a disc in the measurement chamber **17** after passing through the gap **26** between the two parts **23**, **24**, will receive a force toward the other part **23** or **24** in the axial direction. After this pulse the voltages on the two parts **23**, **24** can once again be made equal and the ions will then oscillate with harmonic motion in the potential well of the field in the axial direction. One or both parts **23**, **24** of the outer shaped electrode **16** is then used to detect image current as the ions oscillate back and forward. The Fourier Transform of the signal from the time domain to the frequency domain can thus produce a mass spectrum in conventional manner. It is in this mode of detection with which high mass resolutions are possible.

2. The Mass-Selective Instability (MSI) Mode

The second mode of mass detection involves ejection of the ions from the potential well in the hyper-logarithmic field and collection on a detector.

This mode of operation is analogous to that used in conventional quadrupole ion traps, but differs greatly in that in this device there is no instability in the radical direction.

Although the principal analysis method used in terms of utilising the important advantages of the present invention would be the Fourier Transform mode, there are certain instances where the MSI mode is useful. For example one mass, can be stored for subsequent MS/MS analysis, by ejecting all other masses from the trap, or high intensity signals from unwanted components can be ejected to improve dynamic range.

In this method, the voltage applied to the electrodes **14**, **16** is varied sinusoidally with time as in a quadrupole or quadrupole ion trap device, giving two, possible regimes of mass instability.

a) Parametric Resonance

If the voltage between the inner and outer shaped electrode **14**, **16** of the spectrometer is varied sinusoidally, then the equations describing ion motion within the trap are the well-known Mathieu equations. In a complete analogy with the quadrupole or quadrupole ion trap, the solutions of the equations of motion can be expressed in terms of two parameters a and q, and can be represented graphically on a stability diagram.

Application of the appropriate frequency for a given mass results in excitation of oscillations in the axial direction, and after sufficient excitation results in ejection from the measurement chamber **17**. A convenient means of detection of the ions is collision with a conversion dynode **32** in the outer electrode **16** which generates secondary electrons which can be accelerated away to a detector (FIG. **8**). The main advantage over the quadrupole ion trap is that the magnitude of the radio frequency voltages required are much lower, which means that the mass range of the spectrometer in this mode is effectively unlimited. The mass range of the quadrupole ion trap in conventional scan mode is limited in practice to a few thousand Daltons as very high voltages (>10,000) are required at high mass whereas only a few tens of volts are required in the spectrometer of the present invention.

With this method there are two types of scanning with regard to mass resolution. The first is a rapid scan mode which provides around unit mass resolution. The second regime utilizes the addition of some anharmonic field perturbations which allow the achievement of very high resolutions but at the expense of scan speed. The slower the scan speed the higher the resolution.

b) Resonant Excitation

In this mode of operation the sinusoidal oscillations are applied to one half **23**, **24** of the outer shaped electrode **16** at the resonant axial frequency of a particular mass. As above, both low and high resolution modes of operation are possible. The disadvantage of this mode at low resolution compared to the parametric excitation mode is the presence of a number of side resonances which leads to artefacts. However the resonant excitation mode becomes competitive with the parametric excitation mode at high resolution modes of scanning which make use of anharmonic field perturbations. Again high resolutions are only possible at the expense of scan speed. Whether parametric or resonance excitation is the best MSI mode for high resolution depends on the application in which it is to be used. For example parametric resonance does not show a large dependence on beam width, but resonant excitation provides higher scanning rates at the high resolution due to a faster rate of energy acquisition during excitation.

The main advantage of the spectrometer of the present invention over the prior art type of spectrometers, and in particular the ion Cyclotron Resonance (ICR) specification, is much better detection efficiency at high mass. This arises due to the fact that the signal to noise ratio (S/N) is proportional to the image current frequency in an ICR spectrometer the frequency of oscillation decreases as I/M (M being the mass to charge ratio of the ion). With the spectrometer of the present invention the frequency of oscillation decreases as I/M1/2 and hence decreases much more slowly. Thus the spectrometer of the present invention should realise a 30–100 increase in detection efficiency in the 10–100 k Da range. This high mass capability is important in the application of mass spectrometers to biological compounds.

Comparatively the spectrometer of the present invention has less mass resolution at low masses (>1000) than the ICR specification. This arises due to the higher field accuracy in the ICR spectrometer.

Furthermore, the space charge effects (related to the number of ions and hence dynamic range) which can be tolerated in the spectrometer of the present invention is greater than can be tolerated in an ICR spectrometer. This arises due to the fact that the ions are distributed along a longer trajectory and there is some shielding of the ions from each other due to the presence of the central electrode.

These comparisons are illustrated graphically in FIG. **9** of the drawings.

It will be appreciated that with the arrangement of the present invention, it is possible to provide a mass spectrometer which is relatively simple and inexpensive to produce which allows high resolution measurements to be made.

It is of course to be understood that the invention is not intended to be restricted to the details of the above embodiment which is described by way of example only.

What is claimed is:

1. A mass spectrometer comprising an ion source to produce ions to be analyzed, electric field generation means to produce an electric field within which said ions can be trapped and detection means to detect ions according to their mass/charge ratio wherein said electric field defines a potential well along an axis thereof and said ions are caused to be trapped within said potential well and to perform substantially harmonic oscillations within said well along said axis, said ions having rotational motion in a plane substantially orthogonal to said axis.

2. A mass spectrometer according to claim **1** wherein the electric field generated is of substantially hyper-logarithmic form and is defined by the following equation:

$$U(r,z)=k/_2[(z-a)^2-r^2/2]+b\ln(r/c)+d$$

where r, z are cylindrical coordinates and a, b, c, d, k are constants with c>O and b, k>O.

3. A mass spectrometer according to claim **2** wherein the field generation means comprises a pair of electrodes having a shape defined by the equations $z_1(r)$ and $z_2(r)$ respectively and a potential defined by the equations $U(r,z_1(r))=U_1$ and $U(r,z_2(r))=U_2$.

4. A mass spectrometer according to claim **3** wherein said electrodes are coaxial, one electrode forming an outer electrode and another forming an inner electrode.

5. A mass spectrometer according to claim **3** wherein at least one of said electrodes comprises from at least two sections positioned adjacent each other with a gap therebetween.

6. A mass spectrometer according to claim **1** in which an ion injection arrangement is provided which generates an injection electric field which injects ions into the electric field produced by the field generation means to be trapped therein.

7. A mass spectrometer according to claim **6** wherein the ion injection arrangement comprises electrodes disposed externally of the field generation means so as to surround at least a part of the Field generation means.

8. A mass spectrometer according to claim **7** wherein said ion injection arrangement comprises a pair of coaxial cylinder electrodes.

9. A mass spectrometer according to claim **7** wherein at least one of said electrodes is adapted to modify the injection electric field to produce a potential well into which ions can pass so as to be is directed into the electric field produced by the field generation means to be trapped therein.

10. A mass spectrometer according to claim **9** wherein after passage into the potential well in the injection fields, a voltage applied to the electrodes is varied to reduce the magnitude of oscillations of the ions within the well thereby allowing the ions to be directed into said field generation means through a gap between said electrodes.

11. A mass spectrometer according to claim **7** wherein the injection electric field produced causes ions to follow a spiral trajectory around an inner of said electrodes.

12. A mass spectrometer according to claim **6** wherein said ion source includes acceleration and focusing means to accelerate and focus said ions into said ion injection arrangement.

13. A mass spectrometer according to claim **12** wherein said acceleration and focusing means comprises a plurality of charged plates.

14. A mass spectrometer according to claim **12** wherein after passing through said acceleration and focusing means, ions are directed through a tubular member.

15. A mass spectrometer according to claim **1** wherein the harmonic oscillations of said ions are excited by variation of a voltage applied to said field generation means.

16. A mass spectrometer according to claim **1** wherein said detection means acts to detect said ions by detection of an image current induced on a part of said electrodes.

17. A mass spectrometer according to claim **1** wherein said ions are excited and ejected from said field for detection.

18. A mass spectrometer according to claim **17** when said detection means detects secondary particles produced by collision of ions with at least a portion of said detection means.

19. A mass spectrometer according to claim **18** wherein said detection means comprises a dynode and a secondary electron detector, said ions after being arranged to collide with said dynode thereby to produce secondary electrons, said secondary electrons being detected by said detector.

20. A mass spectrometer according to claim **1** further including fragmentation means which is operable to split said ions produced by said ion source into smaller ions thereby allowing the spectrometer to operate in MS/MS configuration.

21. A mass spectrometer according to claim **20** wherein said fragmentation means is operable to fragment selected said ions when trapped in said electric field, non-selected ions being ejected from said field.

22. A mass spectrometer according to claim **1** further comprising at least one of electrodes having at least two sections positioned adjacent each other with a gap there between, and an ion injection arrangement which is provided to generate an injection electric field that injects ions into the electric field produced by the field generation means to be trapped therein, and wherein said ion injection arrangement is operable to inject ions into the field produced by said field generation means through said gap in said electrodes.

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