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Brubaker

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[54] **HYPERBOLIC FIELD MASS FILTER**

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[52] **U.S. Cl.** **250/292**
[51] **Int. Cl.** **H01j 39/34**
[58] **Field of Search** .... 250/41.9 DS

[56] **References Cited**

UNITED STATES PATENTS

3,129,327 4/1964 Brubaker 250/41.9
3,371,204 2/1968 Brubaker 250/41.9

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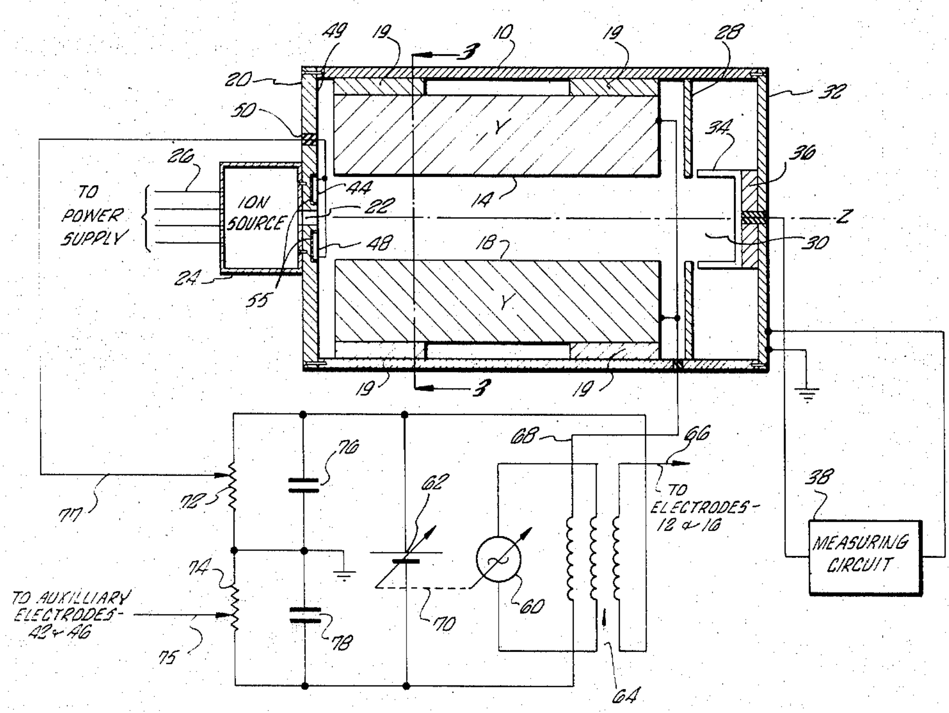
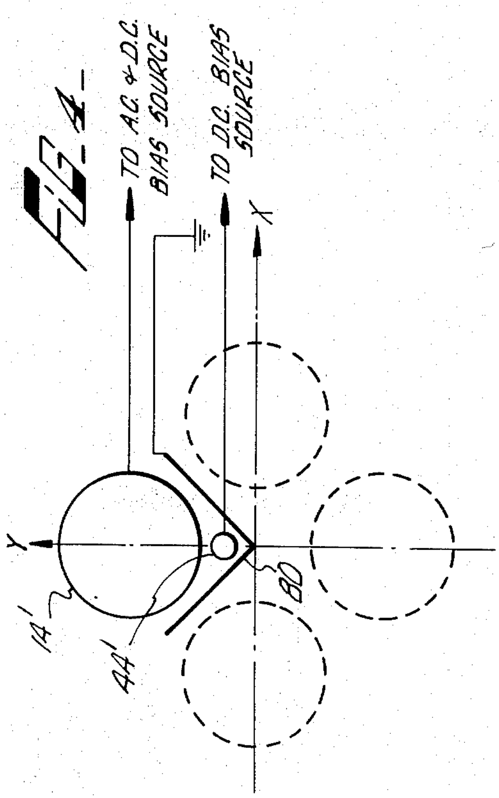
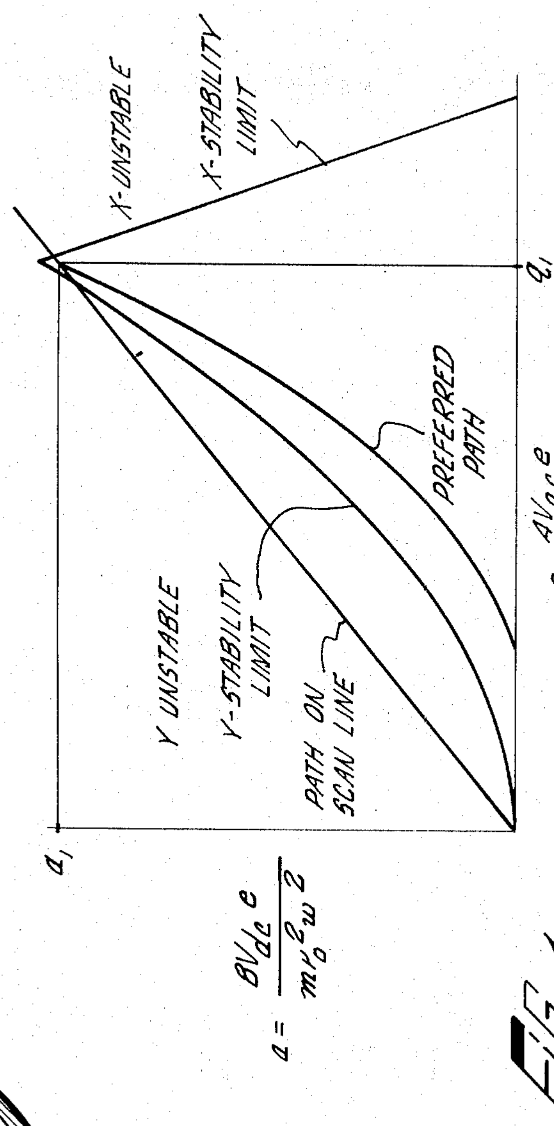
[57] **ABSTRACT**

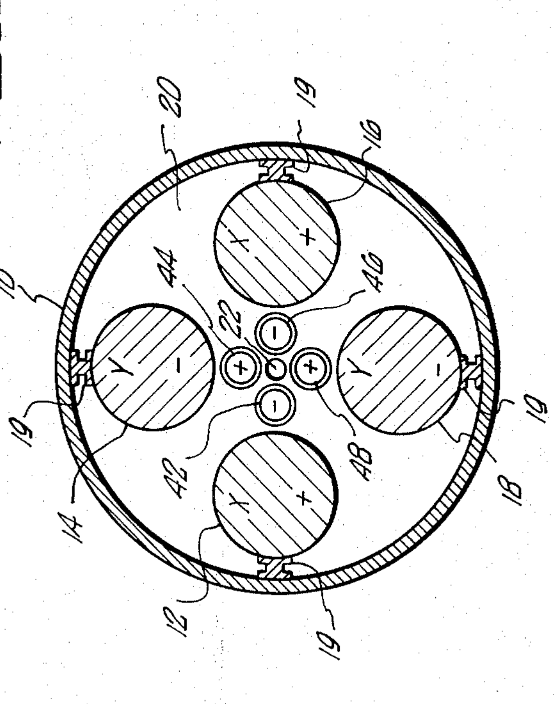
A hyperbolic field mass filter (quadrupole or monopole) is described which includes at least two primary electrodes, an ion entrance aperture, an ion exit aperture and a.c. and d.c. bias sources coupled to the primary electrodes for producing a.c. and d.c. field components between the electrodes. At least one auxiliary electrode is disposed between the primary electrode and the entrance aperture together with means for biasing the auxiliary electrode with d.c. potentials to neutralize the d.c. field produced by the primary electrodes in the vicinity of the entrance aperture.

9 Claims, 4 Drawing Figures









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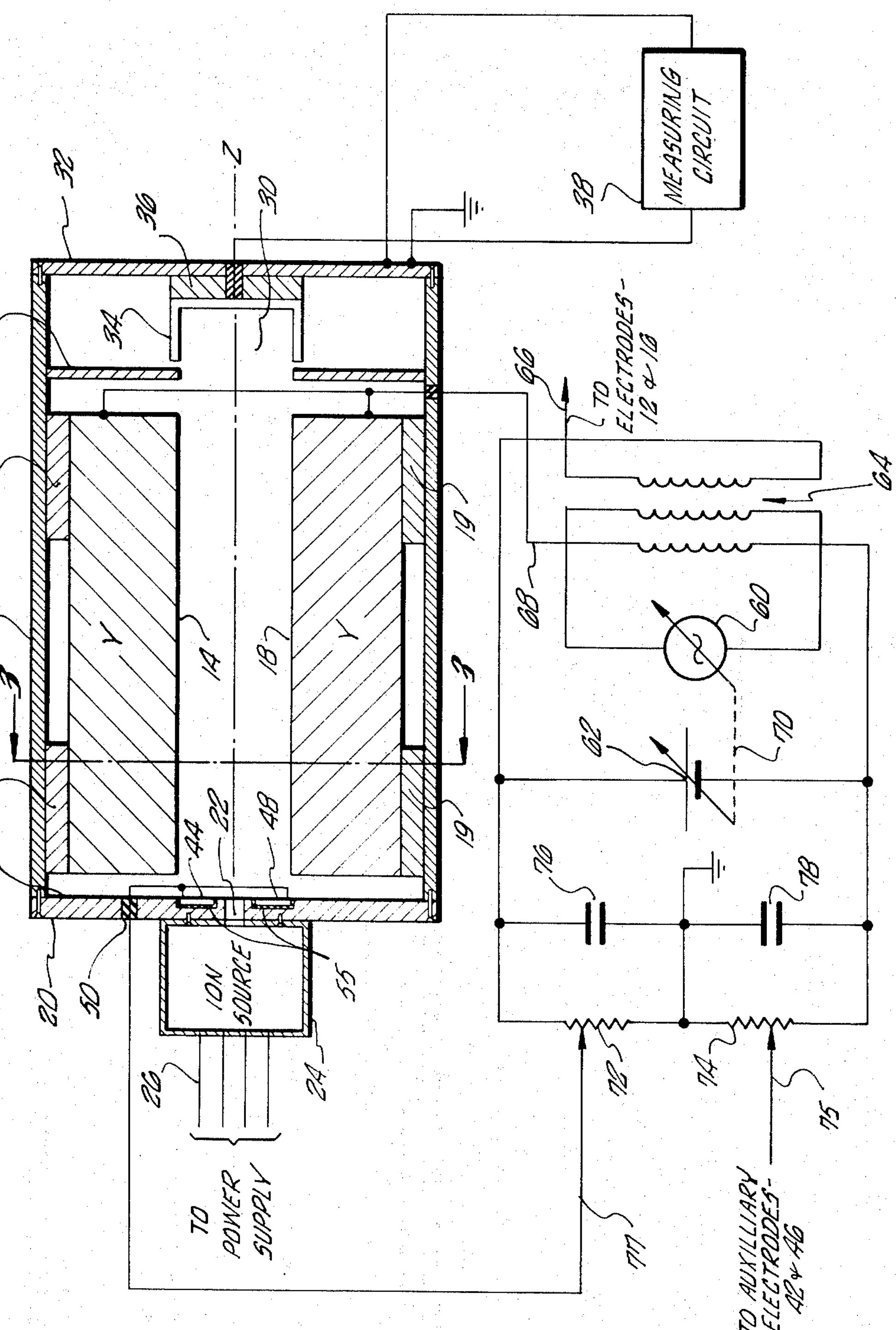

FIG. 2.

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HYPERBOLIC FIELD MASS FILTER

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to quadrupole and monopole mass filters and particularly to the disposition of auxiliary electrodes adjacent to the entrance aperture of the filter and the application of bias potential thereto to provide a delayed d.c. ramp mode of operation.

2. Description of the Prior Art

Quadrupole and monopole mass filters sort out a beam of ions into a spectrum according to the mass (mass to charge ratio) of the incident ions. These mass analyzers are characterized by their utilization of combined a.c. and d.c. fields, as contrasted to the use of magnets by most of the earlier mass analyzer types.

A quadrupole mass filter includes four primary electrodes in the form of parallel cylindrical rods arranged symmetrically about a central axis of the filter. Alternating and direct current voltages are applied in equal but opposite values to neighboring electrodes. The a.c. voltage component is in the radio frequency (r.f.) range.

The theory of operation of the quadrupole mass filter is set forth in the U.S. Pat. No. 3,129,327 which was granted to me in 1964. A summary of the theory is presented here. The force equations for the motion of ions in the combined a.c. and d.c. fields are readily transformed to the standard form of the Mathieu Equation. Solutions of the Mathieu Equation reveal regions of stability and those of instability of the trajectories of the ions. The stability diagram as illustrated in FIG. 1 is divided into alternate bands of stable and unstable portions. The ordinate axis is the dimensionless variable *a*, while the abscissa is the dimensionless variable *q*. These variables are defined in FIG. **1.** For a given a.c. and d.c. excitation level, the loci of the working points for all masses fall on the scan line.

In the ion source the working point is at the origin, since the potentials of the quadrupole electrodes do not penetrate this region. As the transmitted ion passes from the ion source into the prior art filter through the fringe field of increasing strength, the associated working point moves from the origin to the vicinity of the apex along the scan line. In so doing it penetrates deeply into the *y*-unstable region. During this time the ion receives a most undesirable impulse toward the electrodes on the *y* axis. The working point for mass resolved transmitted ions lies just below the apex.

This unstable region can be avoided by operating the filter in a delayed d.c. ramp mode, that is, with a d.c. to a.c. field ratio near the ion entrance aperture which is small as compared to the ratio in the uniform field region in the center of the filter. Under these conditions the working point moves from the origin to the apex of the triangle along a preferred path which lies entirely within the stable portion of the diagram. Thus the undesired *y*-directed impulse is avoided and greatly improved performance of the instrument is obtained.

In the prior art the delayed d.c. ramp has been obtained by the use of an auxiliary set of electrodes which are energized with large a.c. potentials and nearly zero d.c. potentials. This circumstance requires the application of high frequency (r.f.) potentials to these electrodes which are at a negligible d.c. potential. This has been accomplished by using additional high voltage r.f. feedthroughs which pierce the vacuum wall or by the use of resistor and capacitor networks located within the vacuum wall. Either of these expedients adds to the complication of the instrument and increases the a.c. power required to energize it.

SUMMARY OF THE INVENTION

I have discovered a new and simple structure for providing the desired delay d.c. ramp mode of operation for quadrupole or monopole mass filters. In accordance with my invention, the mass filter includes entrance and exit apertures, at least two parallel primary electrodes and bias means for applying d.c. and a.c. voltages to such electrodes to produce a hyperbolic electric field between the electrodes. At least one auxiliary electrode is disposed adjacent to the entrance aperture and bias means are provided for energizing the auxiliary electrodes with d.c. potentials to neutralize the d.c. field produced by the primary electrode in the vicinity of the entrance aperture.

The delayed d.c. ramp is obtained by applying d.c. potentials only to the auxiliary electrode or electrodes. The polarities of these potentials are opposite that of the corresponding primary electrodes. The field resulting from the potentials applied to the auxiliary electrode cancels or neutralizes the d.c. component of the field from the primary electrodes in the vicinity of the entrance aperture. The a.c. field from the primary electrodes is of essentially normal strength in the vicinity of the entrance aperture. Thus the normalized d.c. field is weak reative to the normalized a.c. field in the vicinity of the aperture, but rapidly approaches its normal value at positions more remote from the aperture.

My improved mass filter provides the delayed d.c. ramp mode of operation without increasing the loading of the high frequency (r.f.) power supply. Further, the auxiliary electrodes may be supported on low voltage, high capacitance insulators, and the connecting wires may pass through the vacuum wall on high capacitance feedthrough insulators. The auxiliary electrodes may be conveniently incorporated as a part of the ion source geometry.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a stability diagram illustrating the operating characteristics of a quadrupole or monopole mass filter;

FIG. **2** is a schematic sectional elevation of a quadrupole mass filter and a circuit diagram for providing the bias voltages in accordance with my invention;

FIG. **3** is a sectional view taken along line **3—3** of FIG. **2**; and

FIG. **4** is a schematic end view of a monopole mass filter.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIGS. **2** and **3**, the quadrupole mass filter includes a metallic housing **10** which encloses four primary electrodes **12, 14, 16** and **18.** Electrodes **12** and **16** are designated the X electrodes and electrodes **14** and **18** are designated the Y electrodes. The electrodes are suitably supported by high impedance insulators **19.** The central axis of the filter is designated by Z as is illustrated in FIG. **2.**

The primary electrodes are in the form of cylindrical conducting rods extending parallel to one another and disposed symmetrically about the central axis. The X electrodes lie with their centers in the X-Z plane, and the Y electrodes lie with their centers on the Y-Z plane. Ideally, the electrodes should provide a hyperbolic curvature. However, in practice, a circular curvature is a reasonably satisfactory approximation.

An entrance aperture plate **20**, defining an ion entrance opening **22** centered on the Z axis is secured to one end of the housing by suitable metal screws. Ions of the substance to be analyzed are furnished by an ion source **24** which is secured to the plate **20** by a suitable means. The source **24** is connected to a suitable power supply (not shown) by a cable **26**.

An exit aperture plate **28** is located at the end of the housing **10** remote from the entrance plate **20**. The plate **28** defines an ion exit aperture **30** centered on the Z axis. A rear wall **32** closes the housing and carries an ion collector **34** supported on a feedthrough insulator **36**.

Ions of the selected mass-to-charge ratio enter the filter through the entrance aperture **22**, traverse the filter and impinge on the collector **34**. The ion current may be measured by a conventional measuring circuit **38**. The conductive housing **10** and plates **20**, **28** and **32** are all at ground potential. The interior of the housing is maintained at a low pressure by means of a suitable vacuum pump (not shown).

Four auxiliary electrodes **42, 44, 46** and **48** are positioned symmetrically about the filter-axis Z adjacent the entrance aperture and between a plane defined by the ends of the primary electrodes (adjacent the entrance aperture) and the ion source **24**, as shown in FIG. **2**. The auxiliary electrodes **42, 44, 46** and **48** are mounted on the entrance aperture plate **20** by means of suitable insulators **55**. As is shown, the ion entrance plate **20** is provided with four cavities or recessed portions adjacent the ion entrance aperture **22**. The auxiliary electrodes **42–48** are positioned within individual cavities so that the inner surface of the auxiliary electrodes (facing the interior of the mass filter) are substantially flush with the inner surface **49** of the entrance plate **20**.

Voltage sources **60** and **62** provide a.c. and d.c. potential, respectively, for the primary and auxiliary electrodes as is illustrated in the circuit diagram of FIG. **1**. Diametrically opposed electrodes **12** and **16** are connected via a common lead **66** to the bias sources **60** and **62** through a transformer **64**. The primary electrodes **14** and **18** are connected to the bias sources by means of a lead **68**. The a.c. and d.c. bias sources are shown as being provided with a ganged control arm **70** so that the magnitude of the d.c. potential and the amplitude of the a.c. bias may be varied together to cause ions of a selected mass to be transmitted through the filter to the collector. It should be noted that the ganged control of the a.c. and d.c. bias sources is used for illustration only. The d.c. potential would normally be obtained from the a.c. source **60** by rectification, and would be proportional to the a.c. potential. Such means are described and illustrated in my U.S. Pat. No. 3,129,327. As is illustrated in FIG. **3**, the X electrodes (**12** and **16**) are provided with a positive d.c. potential and the Y electrodes (**14** and **18**) are provided with a negative d.c. potential.

The auxiliary electrodes **42–48** are connected to the d.c. source **62** by means of suitable leads and potentiometers **72** and **74**. A pair of r.f. decoupling capacitors **76** and **78** are connected between opposite terminals of the d.c. source **62** and ground to provide an effective ground for any a.c. signals from the a.c. source **60**. Diametrically opposed auxiliary electrodes **42** and **46** are electrically connected as a pair to the movable tap of the potentiometer **74** via lead **75** for receiving a negative d.c. bias. Auxiliary electrodes **44** and **48** are connected as a pair to the movable tap of potentiometer **72** via lead **77** to receive a positive d.c. bias. The corresponding primary and auxiliary electrodes (**12** and **42**, etc.) are thus provided with d.c. bias voltages of opposite polarity. The taps on potentiometers **72** and **74** are adjusted to produce a d.c. field in the vicinity of the entrance aperture **22** which neutralizes or cancels out the d.c. field produced by the primary electrodes **12–18** so that the d.c. field is substantially zero in the vicinity of the entrance aperture **22**.

The a.c. fields in the vicinity of the entrance aperture are relatively unaffected by the presence of the auxiliary electrodes. Hence, ions entering the filter respond to the a.c. fields promptly, and to the d.c. fields only after they have penetrated more deeply into the filter.

As is illustrated in FIG. **1**, for low values of the a.c. field (near the entrance aperture) even a very small d.c. field will cause the trajectories to be unstable in the Y-Z plane. To increase the stability in the Y-Z plane, I have provided a reverse polarity d.c. bias on the auxiliary electrodes to reduce the d.c. field near the entrance aperture to substantially zero. In this manner I have achieved a highly efficient quadrupole mass analyzer without the need for applying a.c. voltages to the auxiliary electrodes to insure that the ions are subjected to a large a.c. component immediately upon entering the analyzer. This structure eliminates the need for high frequency leads or insulators for the auxiliary electrodes. Also the auxiliary electrodes may be conveniently mounted within the cavities of the entrance aperture plate **20** with the bias leads **75** and **77** being incorporated into the power supply cable for the ion source.

By mounting auxiliary electrodes **40–48** so that their inner surfaces are flush with the inner surface of the entrance plate **20**, the auxiliary electrodes do not shield the region of the entrance aperture from the a.c. fields produced by the primary electrodes. This manner of mounting the auxiliary electrodes provides a structure which is simple and inexpensive to manufacture. The auxiliary electrodes are carried by the entrance plate **20** and the ion source and the connecting leads for the electrodes may be integrated into the leads which energize the ion source.

A monopole mass filter is illustrated in FIG. **4** and includes primary electrodes **14'** and **80**. Electrically the monopole mass filter is exactly one-fourth of a quadrupole filter. It was observed by Ulf Von Zahn and reported in Review of Scientific Instruments, Vol. 34, pages 1–4, 1963 that the planes of symmetry in a quadrupole mass filter appear midway between the primary electrodes and that these planes of symmetry are equipotential surfaces. The replacement of three of the primary electrodes with a conducting surface in the form of a 90° angle plate **80** as shown in FIG. **4** provides the same type of hyperbolic field as that provided in the quadrupole mass filter illustrated in FIG. **2**. The primary electrode **14'** is connected to suitable a.c. and d.c. potential sources. Such sources are illustrated in FIG. **4**. The electrode **80** is connected to ground. This geometry adds an additional constraint to those of the normal quadrupole mass filter in that ions can cross the instrument axis (the apex of the electrode **80**) only at the extremities of the filter. Under these conditions the loci of the working points of the transmitted ions lie within a narrow band slightly displaced from the Y-stability limit. The axial velocity of the ions becomes an important factor in determining the transmission of the ions through the filter, and the ratio of d.c. to a.c. potentials is of lesser importance. The use of an auxiliary electrode **44'** which is energized with a d.c. voltage of opposite polarity to the d.c. voltage applied to the electrode **14'** and of sufficient magnitude to neutralize the d.c. field adjacent the entrance aperture permits the monopole filter to also operate in a delayed d.c. ramp mode. The use of an auxiliary electrode and an appropriate bias source to neutralize the d.c. field adjacent the entrance aperture provides the same advantages for a monopole as have been described above for quadrupole filters.

My improved mass filter provides the desired delayed d.c. ramp mode of operation by means of an inexpensive and simple structure. The filter operates at high efficiency as a result of a reduction in the a.c. excitation power required compared to that of the prior art systems of achieving the delayed d.c. ramp mode of operation.

What is claimed is:

1. In a hyperbolic field mass spectrometer including an ion source, an ion detector, means defining ion entrance and exit apertures aligned with a central axis of the spectrometer and positioned adjacent the ion source and detector, respectively, at least two primary electrodes extending parallel to said axis, the ends of said primary electrodes defining a plane substantially normal to said axis adjacent the entrance aperture, at least one of the primary electrodes being in the form of a rod and means for applying d.c. and a.c. voltages between the primary electrodes to produce a hyperbolic electric field therebetween, the improvement which comprises:

a. at least one auxiliary electrode, each auxiliary electrode having a major portion thereof positioned between said plane defined by the ends of the primary electrodes and the ion source so that the a.c. field in the vicinity of the ion entrance aperture produced by the a.c. voltages on the primary electrodes is substantially unaffected by the presence of the auxiliary electrodes, and

b. means including a d.c. voltage source for applying a potential to each auxiliary electrode to neutralize the d.c. field produced by the primary electrode in the vicinity of the entrance aperture.

2. The combination as defined in claim **1** including two pairs of diametrically opposed parallel primary rod electrodes symmetrically spaced about said axis and at least two pair of auxiliary electrodes.

3. The combination as defined in claim **1** wherein the spectrometer includes an entrance plate forming the entrance aperture, the ion source being carried by the entrance plate, the entrance plate defining a cavity adjacent the entrance aperture and means for mounting the auxiliary electrode within said cavity so that the surfaces of the auxiliary electrode and the aperture plate adjacent the primary electrode are substantially coincident, the mounting means including means for electrically insulating the auxiliary electrode from the entrance plate.

4. The combination as defined in claim **3** including two pairs of diametrically opposed parallel primary rod electrodes symmetrically spaced about said axis and two pairs of diametrically opposed auxiliary electrodes, an auxiliary electrode being associated with each primary electrode and means for energizing the auxiliary electrodes to neutralize the d.c. field component produced by the primary electrodes in the vicinity of the aperture.

5. In a multi-pole mass spectrometer the combination which comprises:

a. a housing having an ion entrance plate at one end which defines an ion entrance aperture and an ion exit plate at the other end which defines an ion exit aperture,

b. two pairs of diametrically opposed parallel primary rod electrodes spaced symmetrically about a central axis which extends from the entrance to the exit apertures, the ends of the primary electrodes defining a plane substantially normal to said axis adjacent the entrance aperture,

c. bias means for applying d.c. and r.f. voltages to the primary electrodes to produce a multi-pole electric field between the primary electrodes,

d. an ion source carried by the entrance aperture plate for injecting ions into the spectrometer,

e. an ion detector positioned adjacent the ion exit aperture for detecting ions,

f. at least two pair of auxiliary electrodes secured adjacent the ion entrance aperture plate and electrically insulated therefrom, each of the auxiliary electrodes having a major portion thereof positioned between said plane defined by the ends of the primary electrodes and the ion source so that the a.c. field in the vicinity of the ion entrance aperture produced by the r.f. voltages on the primary electrodes is substantially unaffected by the presence of the auxiliary electrodes, and

f. means for applying a d.c. potential to the auxiliary electrodes which is of opposite polarity to the d.c. voltage applied to the corresponding adjacent primary electrodes to neutralize the d.c. field component produced by the primary electrodes in the vicinity of the entrance aperture.

6. The combination as defined in claim **5** wherein the auxiliary electrodes are positioned between the plane defined by the ends of the primary electrodes and the ion source.

7. The combination as defined in claim **5** wherein the auxiliary electrodes comprise two pairs of diametrically opposed electrodes, each of the auxiliary electrodes being associated with one of the primary electrodes.

8. The combination as defined in claim **7** including a capacitor connected between each pair of auxiliary electrodes and ground to provide a low impedance path for the r.f. voltages.

9. The combination as defined in claim **7** wherein the entrance plate has an inner surface adjacent the primary electrodes, the entrance plate defining at least one cavity adjacent the entrance aperture for receiving the auxiliary electrodes and means for mounting the auxiliary electrodes on the entrance plate so that the inner surface of the entrance plate is substantially coincident with the surface of the auxiliary electrodes adjacent the primary electrodes to prevent the auxiliary electrode from shielding the entrance aperture from the a.c. fields produced by the primary electrodes, the mounting means including means for electrically insulating the auxiliary electrodes from the entrance plate.

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