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MASS ANALYZER USING TWO SPACED, TUBULAR, AND COAXIAL ELECTRODES

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FIG. 1

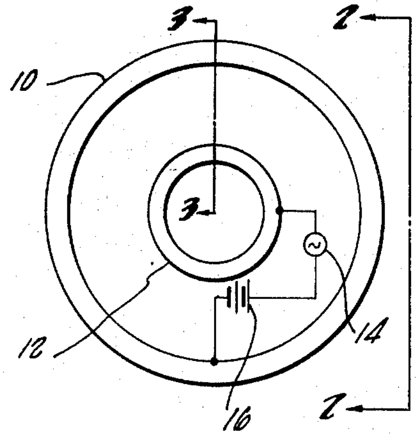


FIG. 2

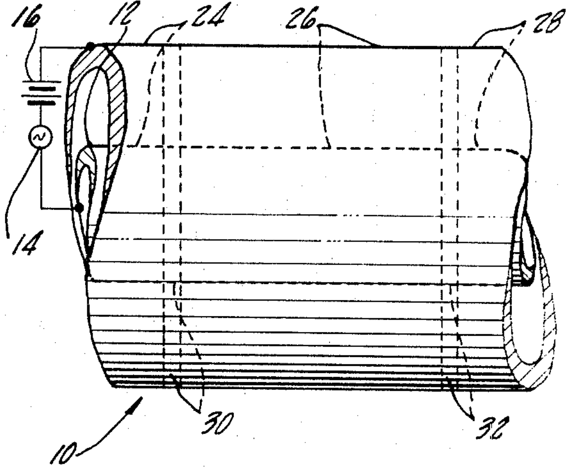
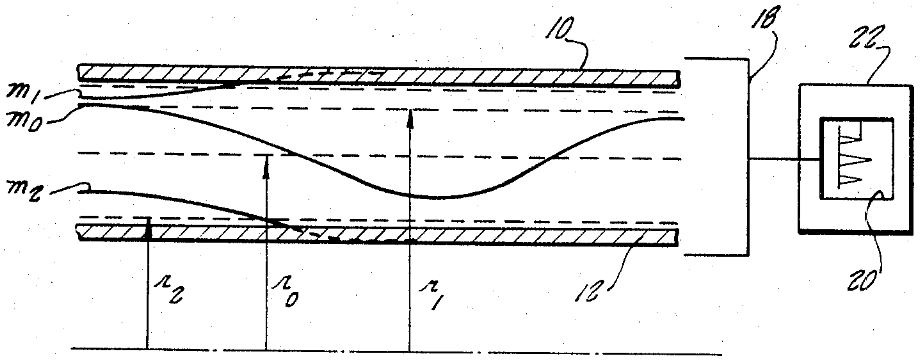


FIG. 3



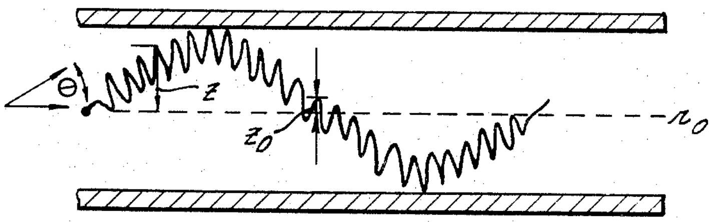


FIG. 4

INVENTOR.
WILSON M. BRUBAKER

BY

Christie, Parker & Hale
ATTORNEYS

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MASS ANALYZER USING TWO SPACED, TUBULAR, AND COAXIAL ELECTRODES

Wilson M. Brubaker, Arcadia, Calif., assignor to Bell & Howell Company, Chicago, Ill., a corporation of Illinois

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U.S. Cl. 250—41.9 **5 Claims**

ABSTRACT OF THE DISCLOSURE

A non-magnetic mass analyzer for separating charged particles according to their mass to charge ratio. The analyzer utilizes the effect of an AC electric field of predetermined amplitude and frequency combined with a DC electric field of predetermined amplitude and polarity created within a confined area to achieve mass separation. Two concentrically oriented electrically conductive cylinders are provided with the combined electric fields being created within the space between the two cylinders. Charged particles of a predetermined mass to charge ratio introduced at the entrance end of the analyzer are transmitted to a charged particle detector at the exit end. Particles of other than the predetermined ratio impinge on the cylinder walls and are discharged thereon.

BACKGROUND OF THE INVENTION

This invention relates to mass analyzers and in particular to a non-magnetic instrument utilizing a specific type of electric field created between two coaxial cylinders to separate charged particles according to their mass to charge ratio.

Analyzers constructed and energized according to the present invention are similar to other non-magnetic analyzer instruments such as monopole or quadrupole mass filters in that mass separation is achieved by means of the effect of a combined AC and DC electric field created in the analyzing portion of the instrument. Because of its characteristics of operation it is contemplated that the present invention will have particular utility as a leak detector in which the apparatus is energized so as to render it sensitive to the presence of ions of helium or some similar tracer element.

In brief, operation of analyzer is accomplished by connecting sources of AC and DC potential to the cylinders of the analyzer to create an electric field in the space between them. Charged particles injected into the region between the two cylinders experience both a translational acceleration along the longitudinal axis of the analyzer and a radial acceleration toward the outer cylinder due to the AC field. It has been found that the magnitude of this radial acceleration is uniquely related to the mass to charge ratio of the charged particle. Transmission of such particles through the analyzer is achieved by balancing the radial acceleration imparted to the particle with an acceleration due to a DC field of proper polarity.

SUMMARY OF INVENTION

The present invention provides a mass analyzer for separating charged particles of different mass comprising a first tube and a second tube located interiorly of the first tube, the second tube having a length which is substantially co-extensive with the length of the first tube. Means are provided for imposing a static electric field of a predetermined magnitude and polarity between the tubes and means are also provided for imposing an alternating electric field of a predetermined magnitude and frequency between the tubes. In addition, means for introducing charged particles into the space between the tubes are provided, together with means for collecting or detecting the

presence of particles emerging from the exit of the analyzer.

In the preferred embodiment of the analyzer of this invention, the cylinders of the analyzer are separated into segments insulated from one another to permit the connection of sources of AC and DC potential of various amplitudes to each of the individual sectors (segment pairs) to reduce the boundary effects at the entrance and exit ends of the analyzer as charged particles traverse the boundaries from the regions of zero field outside the analyzer to the region of strong electric field therewithin.

DESCRIPTION OF THE DRAWING

These and other aspects of the invention will be better understood by reference to the following figures in which:

FIG. 1 is an end view of the analyzer of the present invention, including a schematic representation of an AC and DC source used to energize the analyzer;

FIG. 2 is a view taken along lines **2—2** of FIG. 1;

FIG. 3 is a section view taken along lines **3—3** of FIG. 1 indicating the average position of charged particles of various mass to charge ratios introduced into and passed through the analyzer; and

FIG. 4 is a view taken along line **3—3** of FIG. 1 illustrating the path of motion of charged particles of the selected mass to charge ratios introduced at an angle to the axis of the analyzer.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

A simplified representation of the analyzer of this invention is shown in the end and side views of FIGS. 1 and 2, respectively. As shown in these figures, the analyzer comprises a first tube **10** and a second tube **12** coaxially disposed within the first. Connected between the two cylinders is a source of AC potential **14** and a source of DC potential **16**. The parameters of the amplitude and frequency of the signal from the AC source **14**, and the amplitude of the signal from the DC source **16** will be discussed in more detail subsequently. The polarity of the DC source **16** with respect to inner cylinder **12** is determined by the charge of the particles to be analyzed. For positively charged particles, the positive pole of the battery **16** is connected to cylinder **10.** If used with negatively charged particle, the negative pole of the DC source **16** is connected to the outer cylinder.

Ions directed into the space between the two cylinders encounter the effect of the combined AC and DC field created therein and assume certain characteristic paths of motion dependent upon their mass to charge ratio. FIG. 3 illustrates the average position of ions of three different masses m_0, m_1, and m_2 with the parameters of energization being chosen such that particles of mass m_0 are transmitted by the analyzer. Ions of mass m_0 oscillate about a radius r_0 known as the equilibrium radius for masses m_0 with an amplitude insufficient to bring particles of this mass in contact with either of the two cylinders **10, 12** and hence this ion is transmitted to a collector **18.** Ions of mass m_1 and m_2 have different equilibrium radii due to their different masses and when subjected to the influence of the combined fields within the analyzer are deflected toward and discharged upon the exterior and interior cylinders respectively. Suitable adjustment of the amplitudes of the excitation voltages and/or the frequency of the alternating voltage results in the transmission of masses other than m_0 through the filter producing a signal at the collector **18** and a resultant spectrum **20** such as that shown on recorder **22.**

The principle of operation of the analyzer of this invention is based on the balancing of the acceleration of a charged particle in an AC field by the acceleration in a

DC field. The equation of motion for such a particle in a *uniform* alternating electric field is

$$m\dot{z}=eEac \sin \omega t \tag{1}$$

Where

m=particle mass

z=displacement from equilibrium radius

e=charge on an electron

Eac=peak alternating voltage gradient

ω=angular frequency (radians/sec.)

t=time

Integrating and solving Equation 1 for z yields:

$$z=-(eEac/m\omega^2) \sin \omega t \tag{2}$$

$$=-z_1 \sin \omega t \text{ where } z_1=\frac{eEac(r_1)}{m\omega^2}$$

If the field is slightly non-uniform in space, the motion of the particle will still be essentially sinusoidal, as expressed by Equation 2. However, since the force on the particle is 180° out of phase with the displacement, the impulse given to a particle during any AC cycle is finite and not zero. The effect of such cyclically imposed impulses is to give the charged particle a net acceleration toward the region of weaker field. In the present analyzer this is in the radial direction outward toward exterior cylinder **10**. By balancing this acceleration with an equal but oppositely directed acceleration due to a DC field, the impulse will be balanced and the charged particle will oscillate without radial translation in the applied fields.

For purposes of discussion throughout, the fields and parameters considered will be those existing between two coaxial cylinders. In such a situation the field strength at any point between the two cylinders will be designated $E_{ac}(r)$ or $E_{dc}(r)$ to designate the field strength at any particular radius measured from the center of the coaxial cylinders. If the approximation is made that the field is equal to the impressed voltage divided by the cylinder separation R_2–R_1 (R_1 and R_2 being the radii of the internal and external cylinders respectively), the error is considerably less than 1% if $(R_2-R_1)/R_1$ is 0.1. Such an assumption will be made for purposes of this entire discussion.

In a *non-uniform* AC field such as that created in the space between two coaxial cylinders having an AC source connected between them, the force on a charged particle situated in such a space is somewhat different from that in a uniform field. If a particle in such a field has an average radial position of

$$r_1=(1+\beta)r_0 \tag{3}$$

where r_0 is the radius at a point midway between the cylinders and β is the fractional displacement of the particle from its equilibrium radius and under the influence of a non-uniform AC field the particle is executing pseudo-sinusoidal oscillations about this radial position, then at any instant of time its position is given by

$$r=(1+\beta)r_0-\frac{z_0}{(1+\beta)} \sin \omega t \tag{4}$$

where z is the amplitude of oscillations of a particle about its equilibrium radius r and z_0 is the value of z about r_0 (FIG. 4).

The force on the particle in such a field can be written as

$$m\ddot{r}=eEac(r) \sin \omega t \tag{5}$$

Solving and integrating the preceding expression, the average acceleration which the particle experiences as a result of its motion in the non-uniform alternating field becomes

$$\overline{a_{ac}} \neq \frac{(e/m)(z_0/r_0)E_{ac}(r_0)}{(1+\beta)^3} \tag{6}$$

The preceding equation expresses the effective acceleration experienced by a charged particle as it moves in response to a non-uniform AC field. If this acceleration is balanced by an equal but oppositely directed acceleration in a DC field, the charged particle will experience no net acceleration in the radial direction. As shown above, the acceleration due to an AC field is outwardly directed for a charged particle of either polarity. The direction or polarity of a balancing DC field is dependent upon the sign of the charge of the particle. For positively charged particles the DC field is directed inwardly (positive pole of DC source is connected to outer cylinder) and vice versa for negatively charged particles.

The following analysis of the motion of charged particles in a combined AC and DC field assumes that the charge on the particle is positive. The acceleration in the DC field is given by the expression

$$a_{dc}=(e/m)E_{dc}(r_0)/(1+\beta) \tag{7}$$

equating this expression to the acceleration resulting from motion in an AC field as given by equation (6):

$$(e/m)E_{dc}(r_0)/(1+\beta) =(e/m)(z_0/r_0)E_{ac}(r_0)/(1+\beta)^2 \tag{8}$$

Simplifying the preceding equation, it becomes

$$E_{dc}(r_0)/E_{ac}(r_0)=(z_0/r_0)/(1+\beta)^2 \tag{9}$$

For $\beta=0$, the preceding equation gives the excitation conditions which are required for the AC and DC accelerations to be balanced. For a given ratio of DC to AC voltages and a given frequency of excitation, the left side of the Equation 9 is constant. Substituting the value of z (Equation 2) for z_0, the right side of Equation 9 becomes

$$eEac(r_0)/mr_0\omega^2(1+\beta)^2=\text{constant} \tag{10}$$

From this equation it is noted that for a given analyzer geometry pattern and excitation conditions, the conditions of equal acceleration in the AC and DC fields require that

$$m_1r_0^2(1+\beta)^2=c_1 \text{ (a constant)}$$

and

$$m_1r_1^2=c_1=m_0r_0^2 \tag{11}$$

Thus it can be seen that if ions of mass m_0 have stable equilibrium orbits at radius r_0, ions of mass m_1 have stable equilibrium orbits at radius r_1 where

$$m_1m_0=(r_0/r_1)^2 \tag{12}$$

To first order, ions injected into a coaxial analyzer at a radius other than their equilibrium radius (i.e., at a point where the AC and DC accelerations are not balanced) will oscillate about their equilibrium radius with an angular frequency γ.

The value of γ is calculated as follows: A charged particle injected into the space between the cylinder of a coaxial analyzer at a point other than along its equilibrium radius will experience a net acceleration due to the fact that the acceleration due to the AC field and the acceleration due to the counterbalancing DC field are not equal in magnitude and opposite in direction. In such a case, the particle will respond to the difference or net acceleration between the two accelerations due to the two types of fields created within the analyzer

$$(a \text{ net}=a_{ac}-a_{dc})$$

From Equation 6 the acceleration due to the AC field at the equilibrium radius r_0 is

$$a_{ac}=(e/m)(z_0/r_0)Eac(r_0)/(1+\beta)^3 \tag{13}$$

The acceleration due to the DC field (Equation 7) is

$$a_{dc}=(e/m)E_{dc}(r_0)(1+\beta)$$

From Equation 9

$$E_{dc}(r_0)/E_{ac}(r_0)=(z_0/r_0)/(1+\beta)^2$$

Combining the preceding three expressions and subtracting the acceleration due to the DC field from the AC field, the net acceleration experienced by a particle is expressed by

$$a \text{ net} = -2a_0F(\beta) \qquad (14)$$

where a_0=the balance a_{ac} and a_{dc} at r_0

$$F(\beta) = \frac{1+\beta/2}{(1+\beta)^3} \cong 1 \text{ for } \beta \ll 1$$

The preceding expression demonstrates that where an ion is displaced from the equilibrium radius r_0 the forces on the particle are no longer balanced. From Equation 3, β is defined to be the fractional displacement of the particle from its equilibrium radius, i.e., $(\Delta r)/r_0$, and is normally less than 0.1 for typical operating conditions for the analyzer of this invention. Equation 14 further shows that the acceleration experienced by the particle is directed oppositely to this displacement and is proportional to it.

The net acceleration which causes a particle to oscillate slowly about its equilibrium radius r_0 is found by permitting to be a variable. Mathematically expressed, the second derivative of β is

$$\dot{\beta} = \Delta \dot{r}/r_0 \qquad (15)$$

For F(β) equal to unity

$$\dot{\beta} = 2\beta(a_0/r_0) \qquad (16)$$

A solution which satisfies this equation is

$$\beta = A \sin \gamma t \qquad (17)$$

where

$$\gamma^2 = 2a_0/r_0 \qquad (18)$$

Thus it can be seen that ions introduced into the analyzer at some point other than their equilibrium radius or having an increment of radial velocity when introduced at their equilibrium radius will oscillate about this radius in a sinusoidal manner with an angular frequency γ. The preceding analysis of motion can be illustrated in conjunction with FIG. 3. In that figure the equilibrium radius of ions of mass m_0 is r_0. Ions of masses m_1 and m_2 have different equilibrium radii of r_1 and r_2, respectively. Ions of mass m_0 introduced at radius r_1 parallel to the axis will oscillate about r_0 with an amplitude r_1-r_0 and pass through the analyzer without impinging on either cylinder. FIG. 3 also depicts the trajectory envelopes for masses m_1 and m_2 injected into the analyzer along an axis other than their equilibrium radii. In both instances particles of such masses begin oscillation about their equilibrium radii and impinge on one of the two tubes of the analyzer.

It has been found that effective separation of charged particles of different masses is achieved when the separation between the cylinders is large enough to transmit particles of mass m_0 under practical entrance conditions of position and direction, yet close enough that ions of mass m_1 and m_2 have high probability of striking either of the two cylinders and being discharged thereon.

The pertinent design equations relating excitation voltage and frequency, the ratio of DC to AC voltage and the geometrical configuration of the analyzer are derived from the preceding analysis. From Equation 2 the amplitude of oscillations in response to an AC field is

$$z_0 = eE_{ac}(r_0)/m\omega^2$$

For normal dimensions of the analyzer, the potential gradient may be expressed by the ratio of the voltage impressed between the cylinders divided by the distance between them. That is

$$E(r_0) = V_{ac}/(R_2-R_1) \qquad (19)$$

Combining the two preceding expressions

$$v_{ac} = (R_2-R_1)z_0(m/e)\omega^2 \qquad (20)$$

Where the geometry of the analyzer is given and hence the magnitude of z_0 is determined (z_0 is some chosen fraction of R_2-R_1), the preceding equation relates the mass, frequency of excitation and excitation voltage. Applying the potential gradient as expressed in Equation 19 and combining Equation 9 with Equation 20 yields

$$V_{dc}/V_{ac} = (z_0/r_0)/(1+\beta)^2 = z_0/r_0 \text{ since } \beta \ll 1 \qquad (21)$$

which provides the design equation relating the AC voltage to the DC voltage.

For a practical working analyzer, the final design consideration is that the ratio of the frequency of oscillation of the charged particle (γ) about its equilibrium axis to the excitation frequency (ω) must be small. Combining Equations 10, 18, and the definition of z_0 the ratio is

$$\alpha/w = \sqrt{(z_0/r_0)} \qquad (22)$$

Equations 20, 21, and 22 provide the necessary design equations for the analyzer.

Assuming the analyzer of the preceding description is used as a helium mass spectrometer and using the mks system of units, actual values in the preceding equations can be calculated. In addition to choosing helium for the transmitted mass, the dimensions of the cylindrical analyzer are chosen with R_1 equal to 9 cm. and R_2 to 11 cm. In this instance r_0 will be 10 cm. and z_0 is chosen as 5 mm. Our design equations now become

$$V_{ac} = 4 \times 10^{-12}\omega^2$$

$$V_{dc}/V_{ac} = 1/20$$

$$\gamma/\omega = \sqrt{2}/20 \cong 1/14$$

After determining the preceding three values, the steps remaining are to choose operating voltages and frequency. Choosing the peak AC as 400 volts and ω as 10^7 radians/sec., the frequency becomes 1.6 megacycles. For one period of oscillation, i.e., the time in which a transmitted ion returns to its position relative to the equilibrium radius that it possessed upon entry, the transit time of the ion becomes 4.4 microseconds for the operating values chosen. The energy of helium ions which will traverse a filter L centimeters in length in 4.4 microseconds is

$$V = L^2/10$$

demonstrating that the focusing forces are strong and the transit time for a given mass is short.

Entrance and exit conditions affect the transmission efficiency of an analyzer of the present invention. Since charged particles introduced into the analyzer move from an area of essentially zero electric field into an area of strong electric field such particles receive an impulse which is phase dependent as they enter the strong field. For a filter or analyzer consisting of cylinders of one continuous length, the impulse imparted to a charged particle must be limited, i.e., the phase angle for acceptance of charged particles in order to obtain transmission of a detectable number of ions through the analyzer is restricted to a certain width whose magnitude can be calculated and is dependent upon (a) the maximum radial component of velocity which the charged particle can have as it crosses its equilibrium radius and still be transmitted without striking the electrodes and (b) the phase angle of the AC field as the charged particle enters the filter.

The impulse imparted to particles admitted to the filter can be limited by a filter according to the dotted configuration shown in FIG. 2. In that figure the outer cylinder **10** and the inner cylinder **12** are separated into segments **24**, **26**, and **28** corresponding, respectively, to the entrance, analyzing and exit portions of the filter. Separating each segment is an angular ring, **30** and **32**, respectively, of a high dielectric material to insulate adjacent cylinder segments. In such an embodiment means for controlling the electrical voltage delivered to each segment from sources **14** and **16** must be provided. Suitable impedance and circuit connections from the two sources to each segment can be provided to apply appropriate potentials to the segments of each sector. Alternatively, three separate sources of AC and DC excitation, each having the desired output signal, can be connected respectively to each of the three segments of the filter. To reduce the impulse imparted to particles entering the analyzer the energization delivered to segment **24** is limited to a relatively small fraction of the electrical voltage provided in the analyzing sector **26**. In this manner, charged particles entering the filter experience a more gradual transfer from a region of zero field to the region of relatively high electric field in the analyzing section of the filter or analyzer. Similarly, the voltage delivered to the exit sector **28** of the filter has a magnitude which is a fraction of that applied to the analyzing sector to reduce the "kick" or impulse as the sorted particles leave the filter.

In addition to the parameters chosen in the illustrative example, other sets of operating parameters can also be chosen, particularly other voltages and frequencies. The values chosen in the illustrative example emphasize the large strength of forces which act on charged particles introduced into the fields within the analyzer. These strong focusing forces cause the particles to return quickly to their equilibrium radii and permit the transmission of charged particles which are injected into the filter with sizeable components of radial velocity.

In normal circumstances large entrance apertures to the analyzer are to be used. Since the sensitivity of the instrument to variations in entrance velocity is small, ions introduced into the analyzer are normally subjected to strong accelerating electric fields prior to entrance into the filter. This enables the use of ion sources of high sensitivity. The end result of these factors is the ability to readily achieve large transport currents.

What is claimed is:

1. A mass analyzer for separating charged particles of different masses comprising:

- a first elongated, hollow, tubular electrode having a longitudinal axis;
- a second elongated, tubular electrode located interiorly and coaxially of the first electrode, the two electrodes defining an annular, cylindrically shaped mass analyzing region between adjacent surfaces of the electrodes;
- means for imposing a static electric field of a predetermined magnitude and polarity between the electrodes;
- means for imposing an alternating electric field of a predetermined magnitude and frequency between the electrodes; the ratio of the static electric field and the alternating electric field being chosen with respect to the dimensions of said electrodes such that charged particles of a specific mass are transmitted through the analyzer;
- means for introducing charged particles into the analyzing region in a direction generally parallel to the longitudinal axis of the first electrode at one end of the analyzer; and
- means for collecting charged particles of said specific mass located at the end of the analyzing region opposite the charged particle introducing means.

2. An analyzer according to claim **1** wherein the tubular electrodes are cylinders.

3. A mass analyzer according to claim **2** wherein each of the cylinders is segmented into a plurality of coaxial sectors, each of said sectors being separate from adjacent sectors by a dielectric medium.

4. A mass analyzer according to claim **3** including means for creating a static electric field of a predetermined magnitude and polarity between each corresponding inner and outer cylinder sectors of the analyzer and means for creating an alternating electric field of predetermined magnitude and frequency between each corresponding inner and outer cylinder sectors of the analyzer.

5. A mass analyzer for separating charged particles of different masses comprising:

- a first hollow cylinder;
- a second cylinder located interiorly of the first cylinder and coaxially therewith;
- means for imposing a static electric field of a predetermined magnitude and polarity between the cylinders;
- means for imposing an alternating electric field of a predetermined magnitude and frequency between the cylinders;
- means for introducing charged particles into the space between the cylinders in a direction generally parallel to the longitudial axis of the cylinders at one end of the analyzer; and
- means for collecting charged particles of a predetermined mass located at the end of the analyzer opposite the charged particle introducing means wherein the analyzer is operated substantially according to the relationships:

$$V_{ac}=(R_2-R_1)z_0(m/e)\omega^2$$

$$V_{dc}/V_{ac}=(z_0/r_0)/(1+\beta)^2$$

and

$$\gamma/\omega=\sqrt{2}(z_0/r_0)$$

where V_{ac} is the peak alternating voltage, V_{dc} is the peak static voltage, R_2 is the radius of the first cylinder, R_1 is the radius of the coaxial cylinder located interiorly of the first cylinder, r_0 is the distance between the outer and inner cylinder corresponding to the equilibrium radius of the charged particle of predetermined mass, z_0 is the amplitude of oscillation of the charged particle at r_0, m is the mass of the charged particles to be transmitted, e is the electric charge on an electron, β is the fractional displacement of the particle from r_0, γ is the angular frequency of oscillation of the particle about its equilibrium radius when injected into the analyzer at a point other than its equilibrium radius and ω is the angular frequency of the alternating electric field.

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WILLIAM F. LINDQUIST, Primary Examiner