United States Patent

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[54] MASS SPECTROGRAPH WITH DOUBLE FOCUSING

10 Claims, 4 Drawing Figs.

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[51] Int. Cl. H01j 39/36
[50] Field of Search 250/41.9 ME

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ABSTRACT: To provide for improved energy output and image resolution of Mattauch-Herzog type mass spectrographs, a beam-imaging means, which may be a separate electronic lens, or part of the electric field sector deflection arrangement suitably energized, is located in advance of the beam energy aperture, by a distance such that the exit slit of the ion source is imaged in the plane of the beam energy aperture. A second electronic lens is arranged between the beam energy aperture and the magnetic field sector deflection arrangement, of similar focal length, and arranged to image the target plane of the mass spectrograph at the same plane of the beam energy limiting means, so that the image focused thereon by the first imaging arrangement is received and focused on the target plane by the second electronic lens; the magnetic field sector deflection arrangement is rotated with respect to the electric field sector deflection arrangement by 180° to compensate for the effects of the lenses. The presence of the lenses permits independent adjustment of dispersion angles and energy band width of the ion beams.

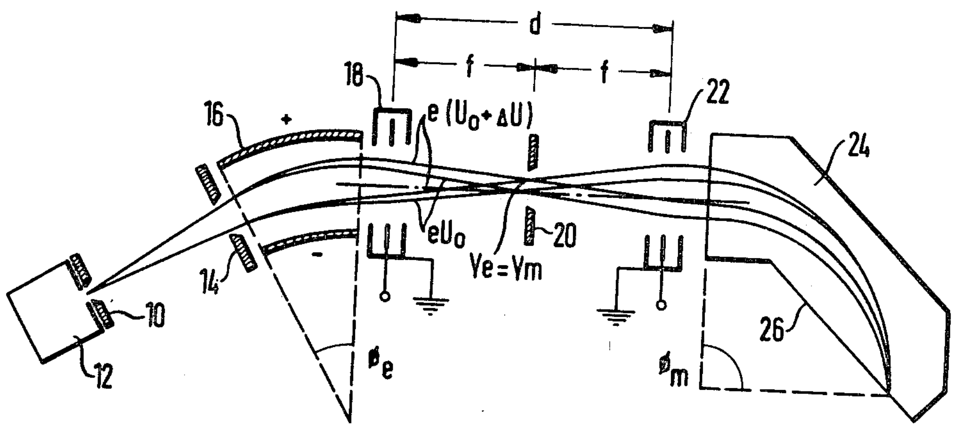
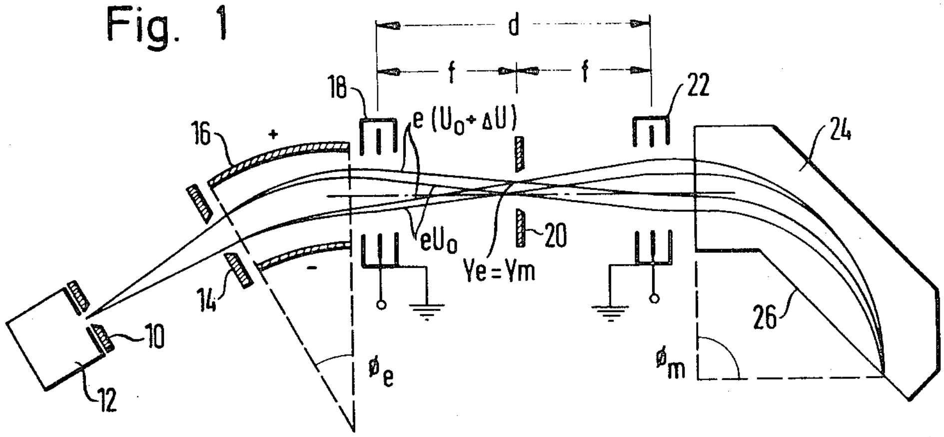


Fig. 1



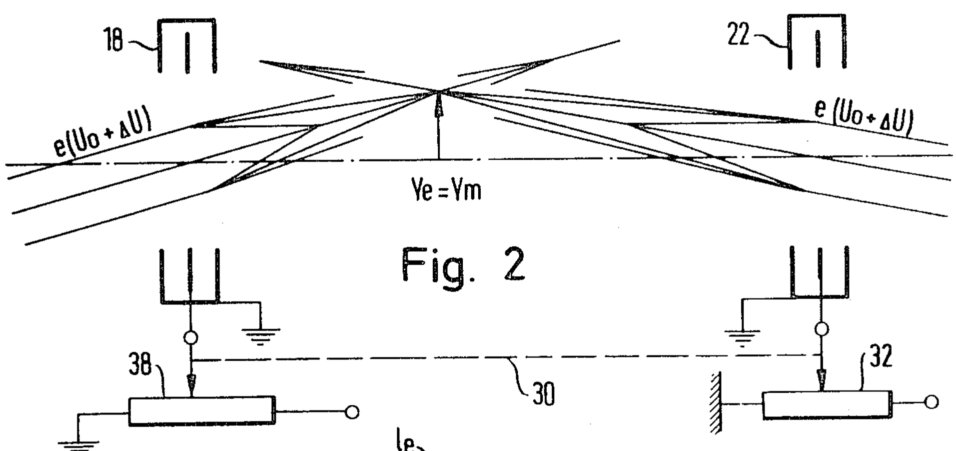


Fig. 2

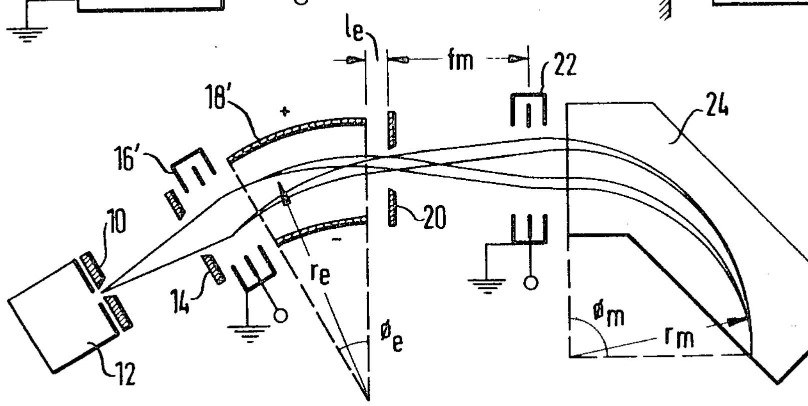


Fig. 3

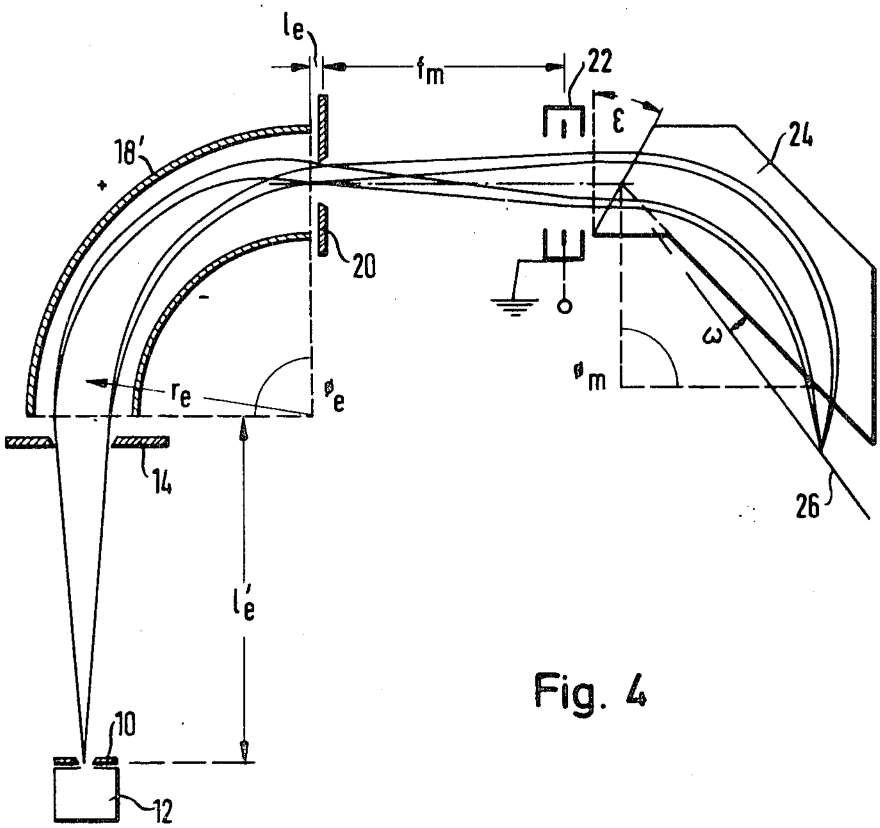


Fig. 4

MASS SPECTROGRAPH WITH DOUBLE FOCUSING

The present invention relates to a mass spectrograph in which the path of ions is so arranged that the ions are focused twice, in order to permit independent adjustment of the energy level ranges as well as of the angle of the beam.

Mass spectrographs of the Mattauch-Herzog type are widely used in industry and research. This type of mass spectrograph is distinguished from other types of mass spectrographs in that all particles can be focused simultaneously along a straight line—see, for example, H. Ewald and H. Hintenberger "-Methoden und Anwendungen der Massenspektroskopie," Chemieverlag Weinheim 1953. The ions are focused twice, that is focusing is obtained by a double-focusing arrangement. Ions which are introduced into the entrance slit in a predetermined, small angular range and which fall within a predetermined energy level, are focused to a mass spectrum as a first approximation. Mass spectrographs of this type do, however, have the disadvantage that it is not possible to independently adjust the ranges of the angle and of the energy level. The reason is seen in that the entrance slit is placed in the focal length of the electrical sector field, so that ions of varying energy which leave the electrical sector field or the analyzer form differently oriented bundles of ions, the ions within the bundles themselves being parallel.

Spectrographs as referred to may limit the permitted range of the angle at the inlet side of the electrical sector field by a diaphragm opening. An aperture or opening between the electrical and the magnetic sector field can limit the energy ranges of the ions. This aperture may be referred to as an energy diaphragm, and it functions as a beam energy limiting means. The energy aperture however decreases the angular range of the ion beam and even if the energy aperture is infinitesimally small, ions which should be limited by the ion aperture can still pass therethrough.

To obtain reasonable resolution of masses, both the angle and the energy range of the ions in the beam must be made small to avoid line spread at the image plane. Usually three image aberrations of second order are present—see, for example, L. A. König and H. Hintenberger, Nucl. Instr. 3, 133 (1958). One is the aperture aberration (α^2 aberration), the other the energy aberration (β^2 aberration) and the third mixed aberration ($\alpha\beta$aberration). Of the three, the mixed ($\alpha\beta$) aberration is the greatest. To reduce this aberration, both the aperture diaphragm as well as the energy aperture, or diaphragm must be made small, substantially decreasing the transmission of ions, that is decreasing their intensity, that is the overall ion energy, or ion current being applied to the target.

It is an object of the present invention to provide a mass spectrograph of the above referred to Mattach-Herzog type in which the energy range and the angular range can be independently adjusted while having an output at the image plane which is highly linear and nondistorted in spite of a high transmitted ion current or energy.

SUBJECT MATTER OF THE PRESENT INVENTION

Briefly, double focusing is provided. Between the entrance slit and the energy aperture, an electrical beam-imaging means is provided, such as an electrical lens. An electronic lens is arranged behind the energy aperture by a distance equal to its focal length. The magnetic sector field follows this electronic lens and is so poled that the ions are deflected therein in the same sense as in the electrical sector field.

The beam-imaging means may wholly consist of the electrical sector field, which is then so formed and dimensioned that the ions are focused in the plane of the energy aperture. Alternatively, the beam-imaging means may include an electronic lens located either between the entrance slit and the electrical sector field, or behind the electrical sector field, and designed and dimensioned to provide ion beams in which the ions of similar energy level are emitted in parallel, the further electronic lens being located the entrance side to the energy aperture by a distance equal to its focal length.

The focal lengths of one, or both of the electrical lenses are preferably adjustable, independently or conjointly.

The invention will be described by way of example with reference to the accompanying drawings, wherein:

FIG. 1 is a schematic presentation illustrating one example of the structure of the present invention;

FIG. 2 is a presentation of the theoretical path of the beams in a portion of the mass spectrograph of FIG. 1;

FIG. 3 is a schematic presentation of a different embodiment of the present invention; and

FIG. 4 is a schematic presentation of an arrangement in which the sector field images the entrance slit in the plane of the energy aperture.

The mass spectrograph of FIG. 1 has an entrance slit **10** to which ions are applied from an ion source **12**, schematically indicated only, and known in the art. In the direction of the path taken by the ions, the structure then includes: an aperture **14**, located immediately in front of an electrical field sector deflection arrangement **16**. Behind the electrical field sector deflection means **16** is a first electronic lens assembly **18** which focuses ions into the plane of an energy aperture **20**. The ions emitted from the electrical sector field are parallel, but randomly oriented bundles of varying energy, which are now all focused on aperture **20**. The distance between energy aperture **20** and lens **18** is equal to the focal length f of the lens **18**. A second, electronic lens **22**, located by a distance equal to its focal length from aperture **20**, which preferably is the same as the focal length f of the first lens, is located behind the energy aperture **20** and which again restores the parallel relationships of the ion bundles. The parallel ion bundles are then introduced into a magnetic field sector deflection means **24**, which is limited at one of its end planes by an imaging plane **26**, for example a photographic plate.

The mass spectrograph of the present invention thus differs from the known instruments of this type by the presence of the lenses **18**, **22**; additionally, the magnetic sector field **24** is rotated with respect to the mean entrance direction of the ions by 180°, so that the ions are deflected in opposite sense by the electrical and magnetic sector fields.

Energy focusing without lenses **18** and **22** is obtained from the following relationship $L_2=N_2$ (1)
in which L_2 is the angular dispersion coefficient of the electrical sector field and N_2 is the angle-dispersion coefficient of the magnetic sector field—see, for example, the above referred to literature reference by König and Hintenberger.

When ions having an energy eU_o leave the electrical sector field **16** parallel to the exit axis then the paths of the ions having an energy level $e(U_o+\Delta U)$ are inclined with respect to the output axis by an angle

$$\gamma_e=L_2\,\Delta U/2\,U_o \qquad (2)$$

Analogous considerations arise with respect to N_2 for the magnetic sector field, if one considers the ion beams coursing counter the actual direction of the beam from the focusing point in the imaging plane **26**. The relationship for the angle γ_m of these ion beams with respect to the entrance axis of the magnetic sector field (which is coincident with the exit axis of the electrical sector field) will be as follows:

$$\gamma_m=N_2\,\Delta U/-2\,U_o \qquad (3)$$

Contrary to the known mass spectrograph of the above referred to type, the two electrical lenses **18**, **22** are located between the electrical sector field **16** and the magnetic sector field **24**. The first lens **18** images an intermediate image of the entrance slit **18** in its focal plane which is coincident with the plane of the energy aperture **20**. Ions of energy eU_o are focused at the axis of the energy aperture. Ions having an energy $e(U_o+\Delta U)$ are focused by a distance

$$y_e=f\quad \gamma_e=f\,L_2\,\Delta U/2\,U_o \qquad (4)$$

in which f is the focal length of lens **18** which, in the example illustrated in FIG. 1, is equal to half of the distance d between the two lenses **18** and **22**.

Let it be assumed, for purposes of discussion, that ions of a predetermined mass are emitted from the imaging plane **26** of the magnetic sector field **24** and travel counter the actual direction of the ion path. Let it be further assumed, for purposes of discussion, that ions of energy eU_o are focused by lens **22** on the axis indicated in FIGS. **1** and **2** in the chain-dotted line, then ions having an energy $e(U_o+\Delta U)$ are focused at a distance

$$y_m=f \quad \gamma_m=f\, N_2\, \Delta u/2\, U_o \quad (5)$$

In order to obtain energy focusing, $y_e=y_m$, and thus

$$L_2=N_2 \quad (6)$$

which, as will be seen is the same as the relationship (1) above. The mathematical requirements of the known mass spectrographs are thus complied with except for the sign. A positive sign indicates that the deflection in both cases would be in the same direction or sense, so that, by rotating one of the fields with respect to the other by 180°, the structure of the system of FIG. **1** will meet all mathematical requirements. All other parameters of the mass spectrograph, particularly those of the electrical and magnetic sector field may be dimensioned as is well known in apparatus of this type.

The energy aperture **20** will determine in the mass spectrograph in accordance with the present invention the energy level range independent of the beam aperture, due to the presence of the two lenses **18**, **22**, located symmetrically with respect to the opening of the energy aperture **20**, in accordance with FIG. **1**. Introducing the two lenses **18**, **22**, has the further advantage that fine focusing and fine adjustment can be done entirely electrically. Mass spectrographs of the above referred to type, as known, require additionally a mechanical displacement of the entrance slit in order to fine-focus the beam. Fine adjustment of energy focusing, as is known, is done by moving the grounding point of the electrical sector field, which however, usually again changes the directional focusing. In mass spectrographs of the present invention, no mechanical motion of the entrance slit is necessary and energy focusing can be achieved as noted, independently of the directional focusing.

Use of two lenses provides for double focusing of ions of energy $e(U_o+\Delta U)$, when the intermediate image projected by the first lens is coincident with the theoretical image of ions which would be emitted from the imaging plane **26**, if they would travel backwards, through the magnetic sector field. As seen in FIG. **2**, in which the theoretical intermediate image is indicated by a vertical arrow, coincidence of this theoretical intermediate image can be readily obtained by adjustment of the focal length of the two lenses.

In order to obtain double focusing of all masses along a straight line in imaging plane **26**, it is only necessary to so adjust and design the apparatus that ions having the same energy enter the magnetic field in parallel and that, considering the ion path backwards, the lens **22** in advance of the magnetic field **24** forms a theoretical intermediate image of the entrance slit **10** which is coincident with the image formed by the other lens, with respect to those ions having the energy $e(U_o+\Delta U)$.

The intermediate image of the entrance slit **10** can be obtained by various arrangements. For example, it is possible to form the intermediate theoretical image solely by the electric sector field, as is being done by a known mass spectrograph—see E. G. Johnson and A.O. Nier, Phys. Rev. 91, 10 (1953).

High transmission and low image aberration is obtained when the combination of an electrostatic lens and a sector field is used, and the lens is used in advance of the sector field—see H. Liebl, J. Appl. Phys. 38, 5277 (1967). An example is seen in FIG. **3** in which an imaging arrangement to obtain a theoretical intermediate image entrance slit **10** is shown. It includes an electric sector field **18'**, and an electronic lens **16'** in advance thereof. The relationship to obtain double focusing for the case, in which only a single lens, namely the one in advance of the magnetic field, is located between the electrical sector field **18'** and the magnetic field, is as follows:

$$r_eK_2+l_eL_2=f_mN_2 \quad (7)$$

wherein

r_e = main radius of the electrical sector field

l_e = distance of the theoretical intermediate image (and thus energy aperture **20**) from the farthest limit of the electrical sector field

f_m = focal length of the lens in front of the magnetic sector field

K_2 = exit dispersion coefficient of the electrical sector field

L_2 = angular dispersion coefficient of the electrical sector field

N_2 = angle dispersion coefficient of the magnetic sector field.

Reference is here also made to the above referred to publication by Konig and Hintenberger.

The above referred to advantage of the exclusively electric fine adjustment of the double focusing is retained in the example of FIG. **3**.

The arrangement described above, as well as the arrangement in accordance with FIG. **1** is well suited to incorporation of the Mattauch-Herzog type mass spectrograph, to obtain independent adjustment of aperture and energy width. To give an example, the invention can be applied to the known double focusing, stigmatically imaging mass spectrograph illustrated in "Zeitschrift für Naturforschung," Vol. 14*a*, Number 2, 1959, pp. 129 to 141. This known mass spectrograph has been modified by locating, in accordance with the arrangement illustrated in FIG. **1**, two electronic lenses between the electrical and the magnetic sector field, and by rotating the magnetic sector field by 180°. The lenses used consist of three cylindrical electrodes of equal inner diameter D, the length (thickness) of the central electrode being $D/2$, and the distance between the center electrode and the outer electrode, each, being $D/4$. A potential is applied to the center electrode of $U_L \triangleq 0.5\ U_o$ (wherein U_o is the energy of the ion/electron discharge). Focal length $f \triangleq 10$ D. If $D=1$ cm., then $f=10$ cm., and the distance d of the two lenses between themselves will be equal to $2f=20$ cm. These two lenses are introduced between the electric and magnetic sector fields, with the energy aperture therebetween. The distances between the electric and magnetic sector fields, at their final limits, are 24.6 cm., and the magnetic field is rotated by 180° about its exit direction.

Other types of lenses may be used, such as extended apertures which, analogous to optical cylindrical lenses focus in only one plane. They will then be so arranged that the focusing plane is coincident with the deflection plane of the mass spectrograph.

Focusing the electronic lenses **18**, **22**, can readily be accomplished by connecting the elements of the electronic lenses to a source of voltage, as schematically indicated in FIG. **2**. Potentiometers **32**, **38** are provided, connected to a source, from which tap points are connected to the center elements of the electrostatic lens. As schematically indicated by the dashed line **30**, the adjustment may be simultaneous, that is the potentiometers **32**, **38** may be gauged, if desired; if not, individual adjustments can be made to provide for individual focusing or for separate balancing of manufacturing tolerances.

FIG. **4** illustrates an arrangement in which the sector field alone images the entrance slit in the plane of the energy aperture. The mathematical relationships for double focusing are identical to those discussed in connection with the embodiments of FIGS. **1** to **3**, namely formula (7) is equally applicable.

Various angles and parameters are indicated in FIG. **4**. These angles, and parameters, in accordance with a calculated example, may be as follows:

$\theta_e=\theta_m=90°$; $\epsilon=26.6°$; $\omega=8.1°$

$l'_e=1.5r_e$; l_e r_e ; $f_m=1.15r_e$

The sector field is a toroidal condenser, having an mean axial radius of curvature $R_e=3.22r_e$. The toroidal condenser, and the axial effect of the lenses in combination with the slanting limits of the magnetic field results in focusing the ions also perpendicularly to the plane of the drawing (see for example: R. Herzog ActaPhys. Austriacae 4 (1950) p. 413). The example of FIG. **4** illustrates that the image plane does not coincide with the trailing limit of the magnetic field, but rather forms an angle ω therewith, which intersects at its origin with the intersection of the beam axis with the leading limit of the magnetic field.

The significance of the remaining dimensions and parameters will be obvious from a consideration of FIG. 4. Focusing of the lens **22** can, again, be readily accomplished by connecting the center electrode to a source of varying potential, for example to the tap point of a potentiometer.

I claim:

1. Mass spectrograph comprising
   an ion source (**12**) generating a beam of ions;
   an entrance slit (**10**) through which said beam of ions passes;
   a target plane (**26**) to receive the ion beam;
   means directing said ion beam from said slit to said target plane (**26**) in a predetermined path;
   electric field sector deflection means (**16**) located in the path of said beam electrically deflecting said beam;
   magnetic field sector deflection means (**24**) located in the path of said beam and magnetically deflecting said beam;
   beam energy limiting means (**20**) located in the path of said beam and disposed between said electric and magnetic field sector deflection means; beams imaging means (**16–18; 16'–18'**) located between the entrances slit and the beam energy limiting means and focusing said beam, in its path, to image said entrance slit in the plane of the beam energy limiting means (**20**) and in advance of said magnetic field sector means (**24**);
   an electric lens (**22**) located in the path of said beam in advance of said magnetic field sector deflection means spaced from said beam energy limiting means (**20**) by a distance equal to its focal length and energized to transform the beam entering said electronic lens (**22**) to a parallel beam so that the beam entering the magnetic field sector deflection means (**24**) is parallel;
   and wherein said magnetic field sector deflection means (**24**) is poled and oriented to deflect said ions in the same sense and direction as said electric field sector deflection means (**16**).
2. Mass spectrograph according to claim **1**, wherein the energy band path width of said beam energy limiting means (**20**) is adjustable.
3. Mass spectrograph according to claim **1**, including a beam width limiting means (**14**) located between the entrance slit (**10**) and the beam-imaging means (**16, 18**).
4. Mass spectrograph according to claim **3**, wherein the beam pass width of said beam width limiting means (**14**) is adjustable.
5. Mass spectrograph according to claim **1**, wherein said beam-imaging means comprises said electric field sector deflection means (**16**) and means energizing said deflection means to simultaneously deflect said ion beam and to focus the image of said slit by said beam in the plane of the beam energy limiting means (**20**).
6. Mass spectrograph according to claim **1**, wherein said beam-imaging means comprises an electronic lens assembly (**18**) located behind said electric field sector deflection means (**16**) in the path of said beam, said electronic lens assembly being spaced from said beam energy limiting means (**20**) by a distance equal to the focal length (*f*) of the electronic lens assembly (**18**).
7. Mass spectrograph according to claim **1**, wherein said beam imaging means comprises an electronic lens assembly (**16'**) located in advance of said electric field sector deflection means (**18'**) in the path of said beam.
8. Mass spectrograph according to claim **7**, wherein the focal length of the beam imaging means (**16'18'**) is adjustable.
9. Mass spectrograph according to claim **1**, wherein the focal length of the electronic lens (**22**) located in advance of the magnetic field sector deflection means (**24**) is adjustable.
10. Mass spectrograph according to claim **1**, wherein the focal length of said beam imaging means (**16, 18**) and said electronic lens (**22**) is adjustable;
    and means (**30**) are provided for conjointly varying the focal length of said beam energy means (**16**) and said electronic lens (**22**).

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