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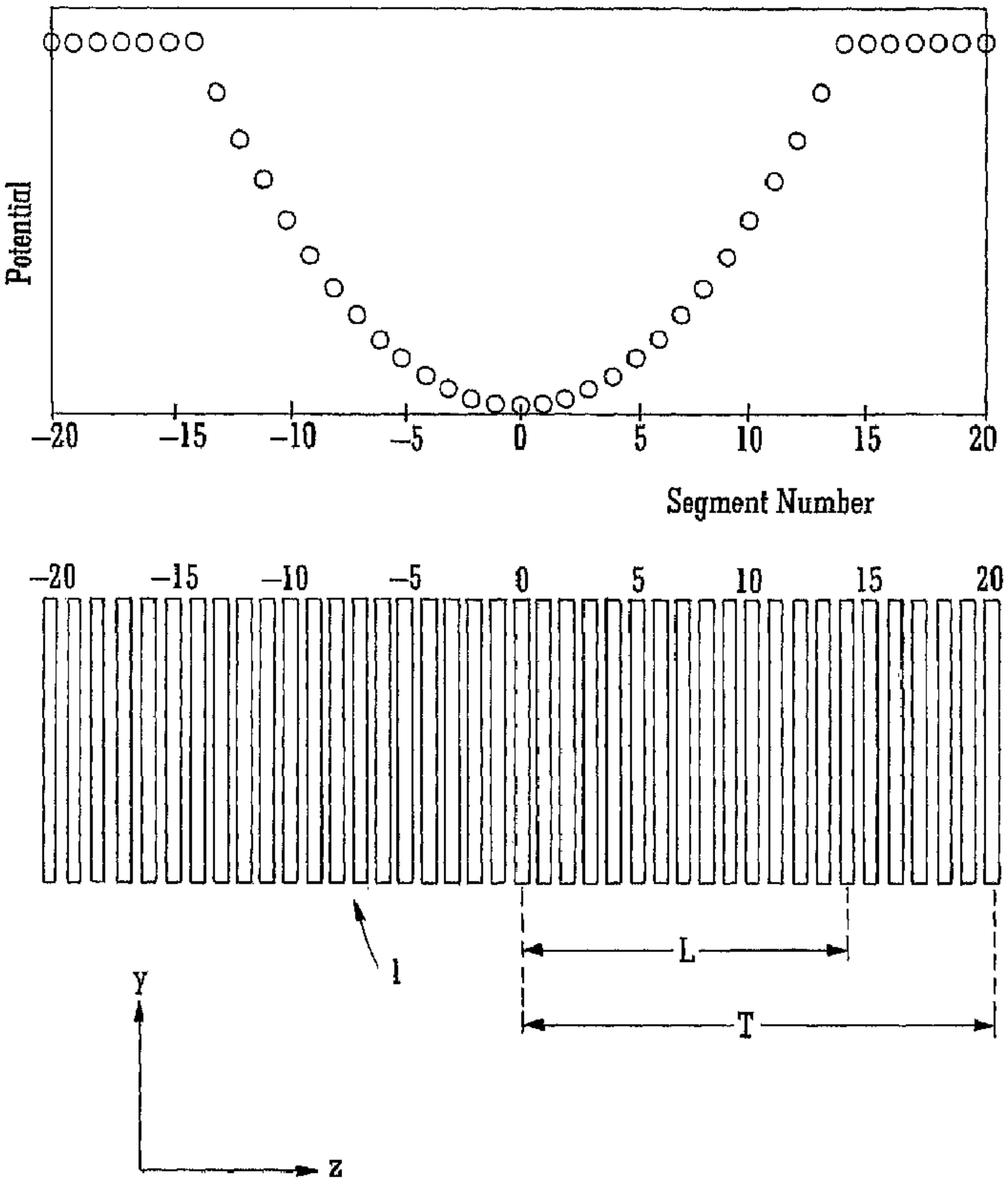

(57) Abrégé/Abstract:

An ion guide or ion trap (1) is disclosed comprising a segmented linear ion guide or ion trap. Ions are confined radially within the ion guide or ion trap (1) by the application of an AC or RF voltage to the electrodes. A static potential well is maintained along at least a

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(57) **Abrégé(suite)/Abstract(continued):**
portion of the axial length of the ion guide or ion trap (1). A time varying homogeneous electric field is applied along at least a portion of the axial length of the ion guide or ion trap (1). The combination of the static axial potential well and the time varying axial homogeneous electric field causes ions to be ejected from the ion guide or ion trap (1) in a substantially non-resonant manner.

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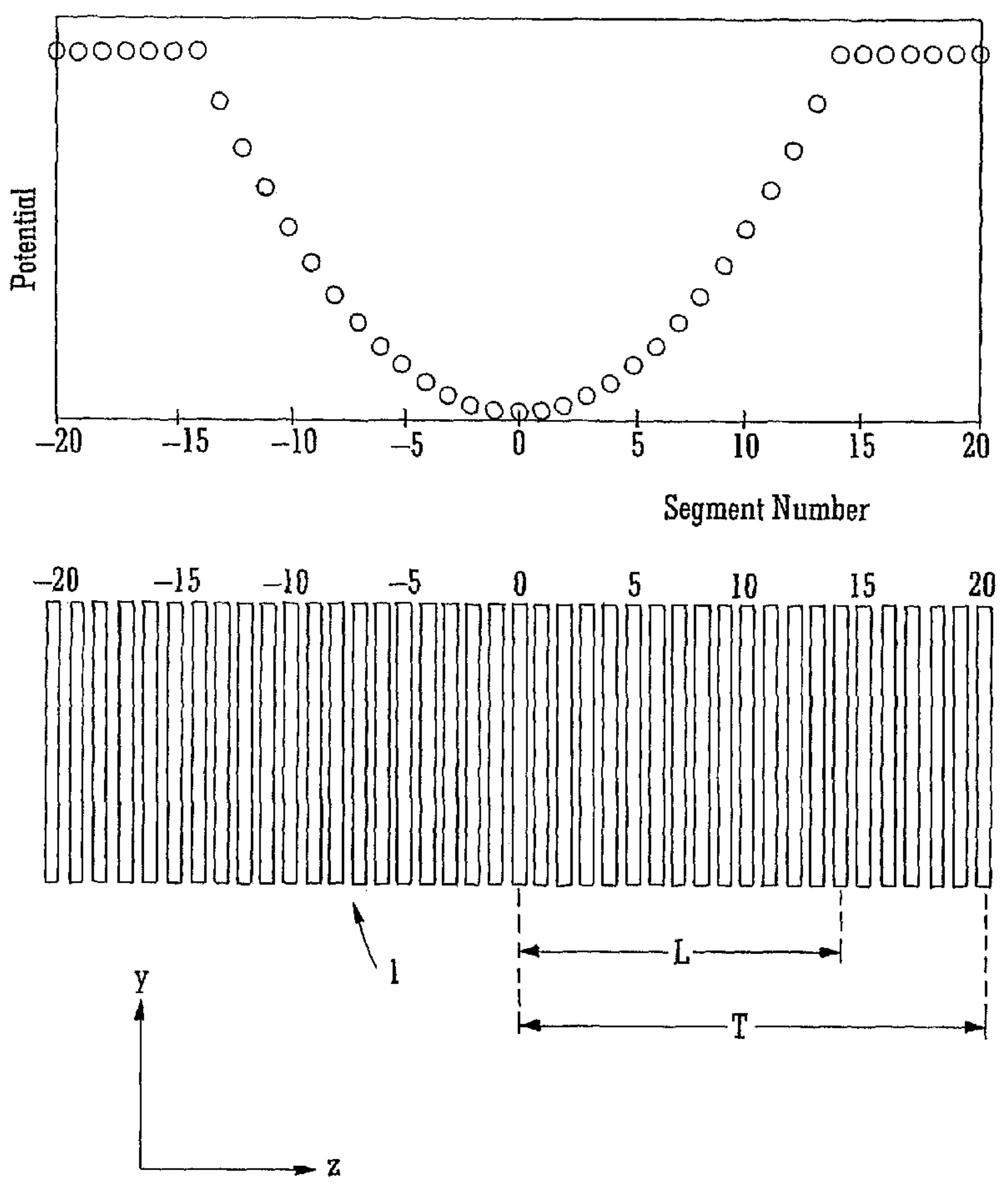

(57) **Abstract:** An ion guide or ion trap (1) is disclosed comprising a segmented linear ion guide or ion trap. Ions are confined radially within the ion guide or ion trap (1) by the application of an AC or RF voltage to the electrodes. A static potential well is maintained along at least a portion of the axial length of the ion guide or ion trap (1). A time varying homogeneous electric field is applied along at least a portion of the axial length of the ion guide or ion trap (1). The combination of the static axial potential well and the time varying axial homogeneous electric field causes ions to be ejected from the ion guide or ion trap (1) in a substantially non-resonant manner.

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MASS SPECTROMETER

The present invention relates to an ion guide or ion trap, a mass spectrometer, a method of guiding or trapping ions and a method of mass spectrometry.

Various ion trapping techniques are known in the field of mass spectrometry. Commercially available 3D or Paul ion traps, for example, provide a powerful and relatively inexpensive tool for many different types of organic analysis. 3D or Paul ion traps generally have a cylindrical symmetry and comprise a central cylindrical ring electrode and two hyperbolic end cap electrodes. In operation an RF voltage is applied between the end cap electrodes and the central ring electrode of the form:

$$V_{0-pk}(t) = V_0 \cos(\sigma t)$$

where V_0 is the zero to peak voltage of the applied RF voltage and σ is the frequency of oscillation of the applied RF voltage.

The physical spacing and shape of the electrodes is such that a quadratic potential is maintained in both the radial and axial directions. Under these conditions ion motion is governed by Mathieu's equation and the various criteria for stable ion trapping are well known to those skilled in the art. The motion of the ions consists of a relatively low frequency component secular motion and a relatively high frequency oscillation or micro-motion which is directly related to the frequency at which the drive voltage is modulated.

Ions may be mass selectively ejected from a 3D or Paul ion trap by: (a) mass selective instability wherein either the amplitude and/or the frequency of the applied RF voltage is altered, (b) by resonance ejection wherein a small supplementary RF voltage is applied to one or both of the end cap or ring electrodes which has the same frequency as the secular frequency of the ions of interest, (c) by application of a DC bias voltage maintained between the ring electrode and the end cap electrodes, or (d) by combinations of the above techniques.

Ions are usually introduced into most commercial 3D or Paul ion traps from an external ion source via a small hole in one of the end cap electrodes. Once within the ion trap, the ions may then be cooled by collisions with a buffer gas to near thermal energies. This has the effect of concentrating the ions towards the centre of the trapping volume of the ion trap. Ions having a specific mass to charge ratio may then be mass selectively ejected from the ion trap. Ejected ions exit the ion trap through a small hole in the end cap electrode opposed to the end cap electrode having an aperture for introducing ions into the ion trap. The ions ejected from the ion trap are then detected using an ion detector.

3D or Paul ion traps suffer from the disadvantage that they possess a relatively limited dynamic range due to the fact that they have a relatively low space charge capacity. Furthermore, extreme care must be taken to ensure that correct conditions are maintained during ion introduction in order to minimize ion losses. As will be understood by those skilled in the art, injecting ions into a 3D Paul ion trap can be particularly problematic.

More recently linear ion traps have been developed and commercialised. Such ion traps generally comprise a multipole rod set wherein ions are confined radially within the ion trap due to the application of a RF voltage to the rods. Ion motion and stability in the radial direction is governed by Mathieu's equation and is well known. Ions may be contained axially within the linear ion trap by the application of a DC or RF trapping potential to electrodes at either end of the multiple rod set. Ion ejection may be accomplished by either ejecting ions radially from the ion trap through a slot in one of the rods or axially by using a combination of radial excitation and inherent field distortions at the axial boundary of the rods.

Linear ion traps generally exhibit increased ion trapping capacities relative to 3D or Paul ion traps and therefore linear ion traps generally exhibit a substantially higher dynamic range. Linear ion traps have an important advantage in that ions may be axially introduced into the ion trap and in some cases axially ejected from the ion trap in a direction which is orthogonal to the radial RF oscillating trapping potential. This enables ions to be transferred more efficiently into and out of the ion trap thereby resulting in improved sensitivity. Linear ion traps are therefore increasingly being preferred to 3D or Paul ion traps due to their increased sensitivity and relatively large ion trapping capacity.

Optimum performance of a linear ion trap which uses radial ejection rather than axial ejection may be achieved using a pure quadrupolar radial potential distribution and accurately shaped hyperbolic rods. However, deviations in the linearity of the radial confining field caused, for example, by mechanical misalignment of the rods can seriously compromise the performance of such a linear ion trap. The provision of slots in the rods of the linear ion trap to facilitate radial ejection can also lead to significant distortions in the radial field. These distortions can further degrade the performance of the linear ion trap. In addition during radial ejection it may be necessary to use more than one ion detector for efficient detection of the ejected ions. This adds to the overall complexity and expense of the ion trap.

It is known to eject ions axially from a linear ion trap. However, the performance of axial ejection of ions from a linear ion trap using fringe fields may also be affected by distortions in the linearity of the radial field. Axial ejection of ions relies upon efficient radial resonance excitation of the ions. If the radial field is non-linear then the resonant frequency will not be constant as the radius of the ion motion increases. Accordingly, the performance of the ion trap in this mode of operation will be compromised. A further problem with axially ejecting ions from a known linear ion trap is that only those ions at or close to the exit fringe field will actually be ejected from the ion trap. Accordingly, the theoretical gains in dynamic range and sensitivity of a linear ion trap relative to a 3D or Paul ion trap may be reduced in practice due to the relatively small region from which ions may actually be ejected from.

US-5783824 (Hitachi) discloses a linear ion trap wherein an axial DC or electrostatic field is maintained along the length of the ion trap. Ions are ejected axially by resonance excitation by the application of a supplementary axial RF potential which oscillates at the fundamental harmonic frequency of the ions which are desired to be ejected. This known linear ion trap has the general advantages of other forms of linear ion trap but in addition forces ions to oscillate axially with a frequency characteristic of their mass to charge ratio. This facilitates axial resonance ejection of ions from the ion trap.

The linear ion trap disclosed in US-5783824 uses resonance excitation to axially eject ions at the fundamental frequency of simple harmonic oscillation determined by an axial quadratic DC or electrostatic potential. However, in practice, it is difficult to generate a true axial quadratic potential due in part to field relaxation effects at the ends or boundaries of the ion trap. Deviations from a true quadratic axial DC or electrostatic potential will result in the frequency of oscillation of the ions being dependent upon the amplitude of oscillation of the ions and this will compromise the performance of the ion trap using resonance ejection.

It is therefore derived to provide an improved ion trap or ion guide.

According to an aspect of the present invention there is provided a linear guide or ion trap comprising:

a plurality of electrodes;

AC or RF voltage means arranged and adapted to apply an AC or RF voltage to at least some of said plurality of electrodes in order to confine radially at least some ions within said ion guide or ion trap;

first means arranged and adapted to maintain one or more DC, real or static potential wells or a substantially static inhomogeneous electric field along at least a portion of the axial length of said ion guide or ion trap in a first mode of operation; and

second means arranged and adapted to maintain a time varying substantially homogeneous axial electric field along at least a portion of the axial length of said ion guide or ion trap in said first mode of operation;

wherein the electric field is varied with time so as to cause ions to oscillate axially along the ion guide or ion trap such that at least some ions are ejected from a trapping region of the ion guide or ion trap in a substantially non-resonant manner whilst other ions are arranged to remain substantially trapped within the trapping region of the ion guide or ion trap.

The AC or RF voltage means is preferably arranged and adapted to apply an AC or RF voltage to at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the plurality of electrodes. According to the preferred embodiment the AC or RF voltage means is arranged and adapted to supply an AC or RF voltage having an amplitude selected from the group consisting of: (i) < 50 V peak to peak; (ii) 50-100 V peak to peak; (iii) 100-150 V peak to peak; (iv) 150-200 V peak to peak; (v) 200-250 V peak to peak; (vi) 250-300 V peak to peak; (vii) 300-350 V peak to peak; (viii) 350-400 V peak to peak; (ix) 400-450 V peak to peak; (x) 450-500 V peak to peak; and (xi) > 500 V peak to peak. Preferably, the AC or RF voltage means is arranged and adapted to supply an AC or RF voltage having a frequency selected from the group consisting of: (i) < 100 kHz; (ii) 100-200 kHz; (iii) 200-300 kHz; (iv) 300-400 kHz; (v) 400-500 kHz; (vi) 0.5-1.0 MHz; (vii) 1.0-1.5 MHz; (viii) 1.5-2.0 MHz; (ix) 2.0-2.5 MHz; (x) 2.5-3.0 MHz; (xi) 3.0-3.5 MHz; (xii) 3.5-4.0 MHz; (xiii) 4.0-4.5 MHz; (xiv) 4.5-5.0 MHz; (xv) 5.0-5.5 MHz; (xvi) 5.5-6.0 MHz; (xvii) 6.0-6.5 MHz; (xviii) 6.5-7.0 MHz; (xix) 7.0-7.5 MHz; (xx) 7.5-8.0 MHz; (xxi) 8.0-8.5 MHz; (xxii) 8.5-9.0 MHz; (xxiii) 9.0-9.5 MHz; (xxiv) 9.5-10.0 MHz; and (xxv) > 10.0 MHz.

The first means is preferably arranged and adapted to maintain at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or >10 potential wells along at least a portion of the axial length of the ion guide or ion trap. The first means may be arranged and adapted to maintain one or more substantially quadratic potential wells along at least a portion of the axial length of the ion guide or ion trap. Alternatively, the first means may be arranged and adapted to maintain one or more substantially non-quadratic potential wells along at least a portion of the axial length of the ion guide or ion trap.

The first means is preferably arranged and adapted to maintain one or more potential wells along at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the axial length of the ion guide or ion trap. According to the preferred embodiment the first means is arranged and adapted to maintain one or more potential wells having a depth selected from the group consisting of: (i) < 10 V; (ii) 10-20 V; (iii) 20-30 V; (iv) 30-40 V; (v) 40-50 V; (vi) 50-60 V; (vii) 60-70 V; (viii) 70-80 V; (ix) 80-90 V; (x) 90-100 V; and (xi) > 100 V.

The first means is preferably arranged and adapted to maintain in the first mode of operation one or more potential wells having a minimum located at a first position along the axial length of the ion guide or ion trap. Preferably, the ion guide or ion trap has an ion entrance and an ion exit, and wherein the first position is located at a distance L downstream of the ion entrance and/or at a distance L upstream of the ion exit, and wherein L is selected from the group consisting of: (i) < 20 mm; (ii) 20-40 mm; (iii) 40-60 mm; (iv) 60-80 mm; (v) 80-100 mm; (vi) 100-120 mm; (vii) 120-140 mm; (viii) 140-160 mm; (ix) 160-180 mm; (x) 180-200 mm; and (xi) > 200 mm.

According to the preferred embodiment the first means comprises one or more DC voltage supplies for supplying one or more DC voltages to at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the electrodes. The first means is preferably arranged and adapted to provide an electric field having an electric field strength which varies or increases along at least a portion of the axial length of the ion guide or ion trap.

The first means is preferably arranged and adapted to provide an electric field having an electric field strength which varies or increases along at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the axial length of the ion guide or ion trap.

The second means is preferably arranged and adapted to maintain the time varying homogenous axial electric field along at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the axial length of the ion guide or ion trap. According to the preferred embodiment the second means comprises one or more DC voltage supplies for supplying one or more DC voltages to at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the electrodes.

The second means is preferably arranged and adapted in the first mode of operation to generate an axial electric field which has a substantially constant electric field strength along at least a portion of the axial length of the ion guide or ion trap at any point in time. Preferably, the second means is arranged and adapted in the first mode of operation to generate an axial electric field which has a substantially constant electric field strength along at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the axial length of the ion guide or ion trap at any point in time.

The second means is preferably arranged and adapted in the first mode of operation to generate an axial electric field which has an electric field strength which varies with time. The second means is preferably arranged and adapted in the first mode of operation to generate an axial electric field which has an electric field strength which varies by at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% with time.

The second means is preferably arranged and adapted in the first mode of operation to generate an axial electric field which changes direction with time. Preferably, the second means is arranged and adapted to generate an axial electric field which has an offset which changes with time.

The second means may be arranged and adapted to vary the time varying substantially homogeneous axial electric field with or at a first frequency f_1, wherein f_1 is selected from the group consisting of: (i) < 5 kHz; (ii) 5-10 kHz; (iii) 10-15 kHz; (iv) 15-20 kHz; (v) 20-25 kHz; (vi) 25-30 kHz; (vii) 30-35 kHz; (viii) 35-40 kHz; (ix) 40-45 kHz; (x) 45-50 kHz; (xi) 50-55 kHz; (xii) 55-60 kHz; (xiii) 60-65 kHz; (xiv) 65-70 kHz; (xv) 70-75 kHz; (xvi) 75-80 kHz; (xvii) 80-85 kHz; (xviii) 85-90 kHz; (xix) 90-95 kHz; (xx) 95-100 kHz; and (xxi) > 100 kHz. Preferably, the first frequency f_1 is greater than the resonance or fundamental harmonic frequency of at least 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95% or 100% of the ions located within an ion trapping region within the ion guide or ion trap. According to the preferred embodiment the first frequency f_1 is at least 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%, 100%, 110%, 120%, 130%, 140%, 150%, 160%, 170%, 180%, 190%, 200%, 250%, 300%, 350%, 400%, 450% or 500% greater than the resonance of fundamental harmonic frequency of at least 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95% or 100% of the ions located within an ion trapping region within the ion guide or ion trap.

According to the preferred embodiment the ejection means is arranged and adapted to alter and/or vary and/or scan the amplitude of the time varying substantially homogeneous axial electric field. The ejection means is preferably arranged and adapted to increase the amplitude of the time varying substantially homogeneous axial electric field. The ejection means may be arranged and adapted to increase the amplitude of the time varying substantially homogeneous axial electric field in a substantially continuous and/or linear and/or progressive and/or regular manner. Alternatively, the ejection means is arranged and adapted to increase the amplitude of the time varying substantially homogeneous axial electric field in a substantially non-continuous and/or non-linear and/or non-progressive and/or irregular manner.

The ejection means is preferably arranged and adapted to alter and/or vary and/or scan the frequency of oscillation or modulation of the time varying substantially homogeneous axial electric field. The ejection means may be arranged and adapted to decrease the frequency of oscillation or modulation of the time varying substantially homogeneous axial electric field. The ejection means may be arranged and adapted to decrease the frequency of oscillation or modulation of the time varying substantially homogeneous axial electric field in a substantially continuous and/or linear and/or progressive and/or regular manner. Alternatively, the ejection means is arranged and adapted to decrease the frequency of oscillation or modulation of the time varying substantially homogeneous axial electric field in a substantially non-continuous and/or non-linear and/or non-progressive and/or irregular manner.

According to the preferred embodiment the ejection means is arranged and adapted to mass selectively eject ions from the ion guide or ion trap. Preferably, the ejection means is arranged and adapted in the first mode of operation to cause substantially all ions having a mass to charge ratio below a first mass to charge ratio cut-off to be ejected from an ion trapping region of the ion guide or ion trap.

According to the preferred embodiment the ejection means is arranged and adapted in the first mode of operation to cause substantially all ions having a mass to charge ratio above a first mass to charge ratio cut-off to remain or be retained or confined within an ion trapping region of the ion guide or ion trap. Preferably, the first mass to charge ratio cut-off falls within a range selected from the group consisting of: (i) < 100; (ii) 100-200; (iii) 200-300; (iv) 300-400; (v) 400-500; (vi) 500-600; (vii) 600-700; (viii) 700-800; (ix) 800-900; (x) 900-1000; (xi) 1000-1100; (xii) 1100-1200; (xiii) 1200-1300; (xiv) 1300-1400; (xv) 1400-1500; (xvi) 1500-1600; (xvii) 1600-1700; (xviii) 1700-1800; (xix) 1800-1900; (xx) 1900-2000; and (xxi) > 2000.

The ejection means is preferably arranged and adapted to increase the first mass to charge ratio cut-off. The ejection means may be arranged and adapted to increase the first mass to charge ratio cut-off in a substantially continuous and/or linear and/or progressive and/or regular manner. Alternatively, the ejection means may be arranged and adapted to increase the first mass to charge ratio cut-off in a substantially non-continuous and/or non-linear and/or non-progressive and/or irregular manner.

According to the preferred embodiment the ejection means is arranged and adapted in the first mode of operation to eject ions substantially axially from the ion guide or ion trap. Preferably, ions are arranged to be trapped or axially confined within an ion trapping region within the ion guide or ion trap, the ion trapping region having a length l, wherein l is selected from the group consisting of: (i) < 20 mm; (ii) 20-40 mm; (iii) 40-60 mm; (iv) 60-80 mm; (v) 80-100 mm; (vi) 100-120 mm; (vii) 120-140 mm; (viii) 140-160 mm; (ix) 160-180 mm; (x) 180-200 mm; and (xi) > 200 mm.

The ion trap or ion guide preferably comprises a linear ion trap or ion guide.

According to an embodiment the ion guide or ion trap comprises a multipole rod set ion guide or ion trap. The ion guide or ion trap may comprise, for example, a quadrupole, hexapole, octapole or higher order multipole rod set. The plurality of electrodes preferably have a cross-section selected from the group consisting of: (i) approximately or substantially circular; (ii) approximately or substantially hyperbolic; (iii) approximately or substantially arcuate or part-circular; and (iv) approximately or substantially rectangular or square. Preferably, a radius inscribed by the multipole rod set ion guide or ion trap is selected from the group consisting of: (i) < 1 mm; (ii) 1-2 mm; (iii) 2-3 mm; (iv) 3-4 mm; (v) 4-5 mm; (vi) 5-6 mm; (vii) 6-7 mm; (viii) 7-8 mm; (ix) 8-9 mm; (x) 9-10 mm; and (xi) > 10 mm.

The ion guide or ion trap is preferably segmented axially or comprises a plurality of axial segments. The ion guide or ion trap may comprise x axial segments, wherein x is selected from the group consisting of: (i) < 10; (ii) 10-20; (iii) 20-30; (iv) 30-40; (v) 40-50; (vi) 50-60; (vii) 60-70; (viii) 70-80; (ix) 80-90; (x) 90-100; and (xi) > 100. Preferably, each axial segment comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 or > 20 electrodes. The axial length of at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the axial segments is preferably selected from the group consisting of: (i) < 1 mm; (ii) 1-2 mm; (iii) 2-3 mm; (iv) 3-4 mm; (v) 4-5 mm; (vi) 5-6 mm; (vii) 6-7 mm; (viii) 7-8 mm; (ix) 8-9 mm; (x) 9-10 mm; and (xi) > 10 mm.

The spacing between at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the axial segments is preferably selected from the group consisting of: (i) < 1 mm; (ii) 1-2 mm; (iii) 2-3 mm; (iv) 3-4 mm; (v) 4-5 mm; (vi) 5-6 mm; (vii) 6-7 mm; (viii) 7-8 mm; (ix) 8-9 mm; (x) 9-10 mm; and (xi) > 10 mm.

According to an embodiment the ion guide or ion trap comprises a plurality of non-conducting, insulating or ceramic rods, projections or devices. The ion guide or ion trap comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 or > 20 rods, projections or devices. The plurality of non-conducting, insulating or ceramic rods, projections or devices preferably further comprise one or more resistive or conducting coatings, layers, electrodes, films or surfaces disposed on, around, adjacent, over or in close proximity to the rods, projections of devices.

According to an embodiment the ion guide or ion trap may comprise a plurality of electrodes having apertures wherein ions are transmitted, in use, through the apertures. Preferably, at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the electrodes have apertures which are substantially the same size or which have substantially the same area. Alternatively, at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the electrodes have apertures which become progressively larger and/or smaller in size or in area in a direction along the axis of the ion guide or ion trap.

According to an embodiment at least 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95% or 100% of the electrodes have apertures having internal diameters or dimensions selected from the group consisting of: (i) ≤ 1.0 mm; (ii) ≤ 2.0 mm; (iii) ≤ 3.0 mm; (iv) ≤ 4.0 mm; (v) ≤ 5.0 mm; (vi) ≤ 6.0 mm; (vii) ≤ 7.0 mm; (viii) ≤ 8.0 mm; (ix) ≤ 9.0 mm; (x) ≤ 10.0 mm; and (xi) > 10.0 mm.

According to an embodiment the ion guide or ion trap may comprise a plurality of plate or mesh electrodes and wherein at least some of the electrodes are arranged generally in the plane in which ions travel in use. Preferably, the ion guide or ion trap comprises a plurality of plate or mesh electrodes and wherein at least 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95% or 100% of the electrodes are arranged generally in the plane in which ions travel in use. The ion guide or ion trap may comprise at least 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 or > 20 plate or mesh electrodes. The plate or mesh electrodes preferably have a thickness selected from the group consisting of: (i) less than or equal to 5 mm; (ii) less than or equal to 4.5 mm; (iii) less than or equal to 4 mm; (iv) less than or equal to 3.5 mm; (v) less than or equal to 3 mm; (vi) less than or equal to 2.5 mm;

(vii) less than or equal to 2 mm; (viii) less than or equal to 1.5 mm; (ix) less than or equal to 1 mm; (x) less than or equal to 0.8 mm; (xi) less than or equal to 0.6 mm; (xii) less than or equal to 0.4 mm; (xiii) less than or equal to 0.2 mm; (xiv) less than or equal to 0.1 mm; and (xv) less than or equal to 0.25 mm.

The plate or mesh electrodes are preferably spaced apart from one another by a distance selected from the group consisting of: (i) less than or equal to 5 mm; (ii) less than or equal to 4.5 mm; (iii) less than or equal to 4 mm; (iv) less than or equal to 3.5 mm; (v) less than or equal to 3 mm; (vi) less than or equal to 2.5 mm; (vii) less than or equal to 2 mm; (viii) less than or equal to 1.5 mm; (ix) less than or equal to 1 mm; (x) less than or equal to 0.8 mm; (xi) less than or equal to 0.6 mm; (xii) less than or equal to 0.4 mm; (xiii) less than or equal to 0.2 mm; (xiv) less than or equal to 0.1 mm; and (xv) less than or equal to 0.25 mm.

According to an embodiment the plate or mesh electrodes are supplied with an AC or RF voltage. Adjacent plate or mesh electrodes are preferably supplied with opposite phases of the AC or RF voltage. The AC or RF voltage has a frequency selected from the group consisting of: (i) < 100 kHz; (ii) 100-200 kHz; (iii) 200-300 kHz; (iv) 300-400 kHz; (v) 400-500 kHz; (vi) 0.5-1.0 MHz; (vii) 1.0-1.5 MHz; (viii) 1.5-2.0 MHz; (ix) 2.0-2.5 MHz; (x) 2.5-3.0 MHz; (xi) 3.0-3.5 MHz; (xii) 3.5-4.0 MHz; (xiii) 4.0-4.5 MHz; (xiv) 4.5-5.0 MHz; (xv) 5.0-5.5 MHz; (xvi) 5.5-6.0 MHz; (xvii) 6.0-6.5 MHz; (xviii) 6.5-7.0 MHz; (xix) 7.0-7.5 MHz; (xx) 7.5-8.0 MHz; (xxi) 8.0-8.5 MHz; (xxii) 8.5-9.0 MHz; (xxiii) 9.0-9.5 MHz; (xxiv) 9.5-10.0 MHz; and (xxv) > 10.0 MHz. The amplitude of the AC or RF voltage is preferably selected from the group consisting of: (i) < 50V peak to peak; (ii) 50-100V peak to peak; (iii) 100-150V peak to peak; (iv) 150-200V peak to peak; (v) 200-250V peak to peak; (vi) 250-300V peak to peak; (vii) 300-350V peak to peak; (viii) 350-400V peak to peak; (ix) 400-450V peak to peak; (x) 450-500V peak to peak; and (xi) > 500V peak to peak.

The ion guide or ion trap preferably further comprises a first outer plate electrode arranged on a first side of the ion guide or ion trap and a second outer plate electrode arranged on a second side of the ion guide or ion trap. The ion guide or ion trap preferably further comprises biasing means to bias the first outer plate electrode and/or the second outer plate electrode at a bias DC voltage with respect to the mean voltage of the plate or mesh electrodes to which an AC or RF voltage is applied. The biasing means is preferably arranged and adapted to bias the first outer plate electrode and/or the second outer plate electrode at a voltage selected from the group consisting of: (i) less than -10V; (ii) -9 to -8V; (iii) -8 to -7V; (iv) -7 to -6V; (v) -6 to -5V; (vi) -5 to -4V; (vii) -4 to -3V; (viii) -3 to -2V; (ix) -2 to -1V; (x) -1 to 0V; (xi) 0 to 1V; (xii) 1 to 2V; (xiii) 2 to 3V; (xiv) 3 to 4V; (xv) 4 to 5V; (xvi) 5 to 6V; (xvii) 6 to 7V; (xviii) 7 to 8V; (xix) 8 to 9V; (xx) 9 to 10V; and (xxi) more than 10V.

The first outer plate electrode and/or the second outer plate electrode are preferably supplied in use with a DC only voltage. Alternatively, the first outer plate electrode and/or the second outer plate electrode may be supplied in use with an AC or RF only voltage. According to an alternative embodiment he first outer plate electrode and/or the second outer plate electrode may be supplied in use with a DC and an AC or RF voltage.

According to an embodiment one or more insulator layers are interspersed, arranged, interleaved or deposited between the plurality of plate or mesh electrodes.

The ion guide or ion trap may comprise a substantially curved or non-linear ion guiding or ion trapping region.

The ion guide or ion trap preferably comprises a plurality of axial segments. The ion guide or ion trap preferably comprises at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95 or 100 axial segments.

According to an embodiment the ion guide or ion trap may have a substantially circular, oval, square, rectangular, regular or irregular cross-section. The ion guide or ion trap may have an ion guiding region which varies in size and/or shape and/or width and/or height and/or length along the ion guiding region.

According to an embodiment the ion guide or ion trap may comprise 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or > 10 electrodes. The ion guide or ion trap preferably comprises at least: (i) 10-20 electrodes; (ii) 20-30 electrodes; (iii) 30-40 electrodes; (iv) 40-50 electrodes; (v) 50-60 electrodes; (vi) 60-70 electrodes; (vii) 70-80 electrodes; (viii) 80-90 electrodes; (ix) 90-100 electrodes; (x) 100-110 electrodes; (xi) 110-120 electrodes; (xii) 120-130 electrodes; (xiii) 130-140 electrodes; (xiv) 140-150 electrodes; or (xv) > 150 electrodes.

The ion guide or ion trap preferably has a length selected from the group consisting of: (i) < 20 mm; (ii) 20-40 mm; (iii) 40-60 mm; (iv) 60-80 mm; (v) 80-100 mm; (vi) 100-120 mm; (vii) 120-140 mm; (viii) 140-160 mm; (ix) 160-180 mm; (x) 180-200 mm; and (xi) > 200 mm.

The ion guide or ion trap preferably comprises means arranged and adapted to maintain in a mode of operation the ion guide or ion trap at a pressure selected from the group consisting of: (i) $< 1.0 \times 10^{-1}$ mbar; (ii) $< 1.0 \times 10^{-2}$ mbar; (iii) $< 1.0 \times 10^{-3}$ mbar; (iv) $< 1.0 \times 10^{-4}$ mbar; (v) $< 1.0 \times 10^{-5}$ mbar; (vi) $< 1.0 \times 10^{-6}$ mbar; (vii) $< 1.0 \times 10^{-7}$ mbar; (viii) $< 1.0 \times 10^{-8}$ mbar; (ix) $< 1.0 \times 10^{-9}$ mbar; (x) $< 1.0 \times 10^{-10}$ mbar; (xi) $< 1.0 \times 10^{-11}$ mbar; and (xii) $< 1.0 \times 10^{-12}$ mbar.

The ion guide or ion trap preferably further comprises means arranged and adapted to maintain in a mode of operation the ion guide or ion trap at a pressure selected from the group consisting of: (i) $> 1.0 \times 10^{-3}$ mbar; (ii) $> 1.0 \times 10^{-2}$ mbar; (iii) $> 1.0 \times 10^{-1}$ mbar; (iv) > 1 mbar; (v) > 10 mbar; (vi) > 100 mbar; (vii) $> 5.0 \times 10^{-3}$ mbar; (viii) $> 5.0 \times 10^{-2}$ mbar; (ix) 10^{-3}-10^{-2} mbar; and (x) 10^{-4}-10^{-1} mbar.

In a mode of operation ions are preferably trapped but are not substantially fragmented within the ion guide or ion trap. According to an embodiment the ion guide or ion trap further comprises means arranged and adapted to collisionally cool or substantially thermalise ions within the ion guide or ion trap in a mode of operation. The means arranged and adapted to collisionally cool or thermalise ions within the ion guide or ion trap is preferably arranged to collisionally cool or to substantially thermalise ions prior to and/or subsequent to ions being ejected from the ion guide or ion trap.

According to an embodiment the ion guide or ion trap preferably further comprises fragmentation means arranged and adapted to substantially fragment ions within the ion guide or ion trap. The fragmentation means is preferably arranged and adapted to fragment ions by Collisional Induced Dissociation ("CID"). According to a less preferred embodiment the fragmentation means may be arranged and adapted to fragment ions by Surface Induced Dissociation ("SID").

The ion guide or ion trap is preferably arranged and adapted in a second mode of operation to resonantly and/or mass selectively eject ions from the ion guide or ion trap.

The ion guide or ion trap is preferably arranged and adapted in the second mode of operation to eject ions axially and/or radially from the ion guide or ion trap.

The ion guide or ion trap is preferably arranged and adapted in the second mode of operation to adjust the frequency and/or amplitude of an AC or RF voltage applied to the electrodes in order to eject ions by mass selective instability.

According to an embodiment the ion guide or ion trap is arranged and adapted in the second mode of operation to superimpose an AC or RF supplementary waveform or voltage to the plurality of electrodes in order to eject ions by resonance ejection.

The ion guide or ion trap is preferably arranged and adapted in the second mode of operation to apply a DC bias voltage to the plurality of electrodes in order to eject ions.

According to an embodiment in a further mode of operation the ion guide or ion trap is preferably arranged to transmit ions or store ions without the ions being mass selectively and/or non-resonantly ejected from the ion guide or ion trap.

In a further mode of operation the ion guide or ion trap may be arranged to mass filter or mass analyse ions.

According to an embodiment in a further mode of operation the ion guide or ion trap may be arranged to act as a collision or fragmentation cell without ions being mass selectively and/or non-resonantly ejected from the ion guide or ion trap.

The ion guide or ion trap preferably comprises means arranged and adapted to store or trap ions within the ion guide or ion trap in a mode of operation at one or more positions which are closest to the entrance and/or centre and/or exit of the ion guide or ion trap.

The ion guide or ion trap preferably further comprises means arranged and adapted to trap ions within the ion guide or ion trap in a mode of operation and to progressively move the ions towards the entrance and/or centre and/or exit of the ion guide or ion trap.

The ion guide or ion trap preferably further comprises means arranged and adapted to apply one or more transient DC voltages or one or more transient DC voltage waveforms to the electrodes initially at a first axial position, wherein the one or more transient DC voltages or one or more transient DC voltage waveforms are then subsequently provided at second, then third different axial positions along the ion guide or ion trap.

The ion guide or ion trap preferably further comprises means arranged and adapted to apply, move or translate one or more transient DC voltages or one or more transient DC voltage waveforms from one end of the ion guide or ion trap to another end of the ion guide or ion trap in order to urge ions along at least a portion of the axial length of the ion guide or ion trap. The one or more transient DC voltages preferably create: (i) a potential hill or barrier; (ii) a potential well; (iii) multiple potential hills or barriers; (iv) multiple potential wells; (v) a combination of a potential hill or barrier and a potential well; or (vi) a combination of multiple potential hills or barriers and multiple potential wells.

According to an embodiment the one or more transient DC voltage waveforms comprise a repeating waveform or square wave.

According to an embodiment the ion guide or ion trap preferably further comprises means arranged to apply one or more trapping electrostatic or DC potentials at a first end and/or a second end of the ion guide or ion trap.

The ion guide or ion trap preferably further comprises means arranged to apply one or more trapping electrostatic potentials along the axial length of the ion guide or ion trap.

According to another aspect of the present invention there is provided a mass spectrometer comprising an ion guide or an ion trap as described above.

The mass spectrometer preferably further comprises an ion source selected from the group consisting of: (i) an Electrospray ionisation ("ESI") ion source; (ii) an Atmospheric Pressure Photo Ionisation ("APPI") ion source; (iii) an Atmospheric Pressure Chemical Ionisation ("APCI") ion source; (iv) a Matrix Assisted Laser Desorption Ionisation ("MALDI") ion source; (v) a Laser Desorption Ionisation ("LDI") ion source; (vi) an Atmospheric Pressure Ionisation ("API") ion source; (vii) a Desorption Ionisation on Silicon ("DIOS") ion source; (viii) an Electron Impact ("EI") ion source; (ix) a Chemical Ionisation ("CI") ion source; (x) a Field Ionisation ("FI") ion source; (xi) a Field Desorption ("FD") ion source; (xii) an Inductively Coupled Plasma ("ICP") ion source; (xiii) a Fast Atom Bombardment ("FAB") ion source; (xiv) a Liquid Secondary Ion Mass Spectrometry ("LSIMS") ion source; (xv) a Desorption Electrospray Ionisation ("DESI") ion source; (xvi) a Nickel-63 radioactive ion source; (xvii) an Atmospheric Pressure Matrix Assisted Laser Desorption Ionisation ion source; and (xviii) a Thermospray ion source.

The mass spectrometer preferably comprises a continuous or pulsed ion source.

The mass spectrometer preferably further comprises one or more further ion guides or ion traps arranged upstream and/or downstream of the ion guide or ion trap. The one or more further ion guides or ion traps are preferably arranged and adapted to collisionally cool or to substantially thermalise ions within the one or more further ion guides or ion traps. The one or more further ion guides or ion traps may be arranged and adapted to collisionally cool or to substantially thermalise ions within the one or more further ion guides or ion traps prior to and/or subsequent to ions being introduced into the ion guide or ion trap.

According to an embodiment the mass spectrometer further comprises means arranged and adapted to introduce, axially inject or eject, radially inject or eject, transmit or pulse ions from the one or more further ion guides or ion traps into the ion guide or ion trap.

The mass spectrometer may further comprise means arranged and adapted to introduce, axially inject or eject, radially inject or eject, transmit or pulse ions into the linear ion guide or ion trap.

The mass spectrometer may further comprise means arranged and adapted to substantially fragment ions within the one or more further ion guides or ion traps.

The mass spectrometer preferably further comprises one or more ion detectors arranged upstream and/or downstream of the linear ion guide or ion trap. The mass spectrometer preferably further comprises a mass analyser arranged downstream and/or upstream of the linear ion guide or ion trap. The mass analyser is preferably selected from the group consisting of: (i) a Fourier Transform ("FT") mass analyser; (ii) a Fourier Transform Ion Cyclotron Resonance ("FTICR") mass analyser; (iii) a Time of Flight ("TOF") mass analyser; (iv) an orthogonal acceleration Time of Flight ("oaTOF") mass analyser; (v) an axial acceleration Time of Flight mass analyser; (vi) a magnetic sector mass spectrometer; (vii) a Paul or 3D quadrupole mass analyser; (viii) a 2D or linear quadrupole mass analyser; (ix) a Penning trap mass analyser; (x) an ion trap mass analyser; (xi) a Fourier Transform orbitrap; (xii) an electrostatic Fourier Transform mass spectrometer; and (xiii) a quadrupole mass analyser.

According to another aspect of the present invention there is provided a method of guiding or trapping ions comprising:

providing an ion guide or ion trap comprising a plurality of electrodes;

applying an AC or RF voltage to at least some of said plurality of electrodes in order to confine radially at least some ions within said ion guide or ion trap;

maintaining one or more DC, real or static potential wells or a substantially static inhomogeneous electric field along at least a portion of the axial length of said ion guide or ion trap in a first mode of operation; and

maintaining a time varying substantially homogeneous axial electric field along at least a portion of the axial length of said ion guide or ion trap in said first mode of operation;

wherein the electric field is varied with time so as to cause ions to oscillate axially along the ion guide or ion trap such that at least some ions are ejected from a trapping region of said ion guide or ion trap in a substantially non-resonant manner whilst other ions are arranged to remain substantially trapped within said trapping region of said ion guide or ion trap.

According to another aspect of the present invention there is provided a method of mass spectrometry comprising the method of guiding or trapping ions as detailed above.

According to another aspect of the present invention there is provided an ion guide or ion trap comprising:

a plurality of electrodes;

first means arranged and adapted to maintain one or more DC, real or static potential wells or a substantially static inhomogeneous electric field along at least a portion of the axial length of said ion guide or ion trap in a first mode of operation; and

second means arranged and adapted to maintain a time varying substantially homogeneous axial electric field along at least a portion of the axial length of said ion guide or ion trap in said first mode of operation;

wherein the electric field is varied with time so as to cause ions to oscillate axially along the ion guide or ion trap such that at least some ions are ejected from a trapping region of said ion guide or ion trap in a substantially non-resonant manner whilst other ions are arranged to remain substantially trapped within said trapping region of said ion guide or ion trap.

The preferred embodiment relates to a linear ion guide or ion trap wherein an AC or RF voltage is applied to the electrodes forming the ion guide or ion trap in order to radially confine ions about the axis of the ion guide or ion trap.

A static DC axial potential well is maintained along at least a portion of the axial length of the preferred ion guide or ion trap. Ions are arranged to be trapped, in use, in the static axial potential well.

According to the preferred embodiment an additional time varying homogeneous axial electric field is maintained along at least a portion of the length of the ion guide or ion trap and is preferably substantially maintained along or across the length of the static axial DC potential well.

The time varying homogeneous electric field has an electric field strength which preferably remains substantially constant along the ion trapping region of the preferred ion guide or ion trap. However, the magnitude of the applied electric field preferably varies with time.

The time varying homogeneous axial electric field is preferably provided by applying DC voltages to the electrodes forming the preferred ion trap or ion guide. It will be appreciated that applying an inhomogeneous AC or RF voltage waveform along the length of the preferred ion guide or ion trap will result in an axial inhomogeneous time varying electric field being generated and hence such an arrangement is not intended to fall within the scope of the present invention.

The application of the time varying homogeneous electric field according to the preferred embodiment in combination with a static DC potential well will cause ions having different mass to charge ratios to begin to oscillate along the axis of the preferred ion guide or ion trap. Ions will oscillate with different characteristic amplitudes which will depend upon the mass to charge ratio of the ion. This principle enables ions to be ejected from the preferred ion guide or ion trap in a substantially non-resonant manner.

Ions can be ejected from the preferred ion guide or ion trap by progressively increasing the maximum amplitude of the axial oscillations of the ions. Ions having a relatively low mass to charge ratio may preferably be caused to oscillate axially with a sufficiently large amplitude such that these ions will then escape from the confines of the static axial potential well. These ions will thus become axially ejected from the ion trapping region of the preferred ion guide or ion trap. The ions are therefore preferably mass-selectively ejected from the preferred ion guide or ion trap in the axial direction and in a substantially non-resonant manner i.e. ions are not being ejected from the preferred ion guide or ion trap by exciting them with a voltage having a frequency which corresponds with the inherent resonance or fundamental resonance frequency of the ions.

For illustrative purposes only a first arrangement is contemplated and will be described in more detail wherein a quadratic potential well is provided along the length of the ion guide or ion trap and the position of the quadratic potential well is then modulated. This is in contrast to the preferred embodiment of the present invention which requires the provision of a static axial potential well. The potential profile according to the first arrangement is varied with time so that the quadratic potential well is effectively being continually passed through and along the axial ion trapping region from one side of the ion guide or ion trap to the other. The axial DC potential well can therefore be considered to vary in a manner such that the minimum of the quadratic axial potential well oscillates axially about a reference point.

According to the first arrangement the location of the minimum of quadratic potential well is varied in a substantially periodic fashion so as to cause ions having differing mass to charge ratios to oscillate at non-resonant frequencies along the axis of the preferred ion guide or ion trap with different characteristic amplitudes. Mass selective non-resonant axial ejection of ions is then achieved by, for example, altering the frequency of the periodic modulation of the axial DC potential well. Alternatively, the amplitude of the oscillation of the axial potential minimum may be varied. This will increase the characteristic amplitude of axial oscillations of the ions. In this manner the amplitude of axial oscillation of ions can be varied such that ions having a desired mass to charge ratio are caused to leave the axial ion trapping region and hence are axially ejected from the ion guide or ion trap. Ions may be sequentially ejected from the ion guide or ion trap and may be detected by an ion detector. This enables a mass spectrum to be produced.

According to the first arrangement the position of the minimum of the quadratic axial potential well may be modulated in a substantially symmetrical manner. Ions are caused to acquire an axial motion related to the frequency of the modulation of the quadratic potential well and the frequency of their motion within the quadratic potential well.

The quadratic potential well is according to the first arrangement modulated at a substantially higher frequency than the characteristic fundamental resonance or first harmonic frequency of ions trapped within the potential well. Accordingly, ions can be considered to be non-resonantly ejected rather than resonantly ejected from the ion guide or ion trap according to the first arrangement.

According to the preferred embodiment the ion guide or ion trap may comprise a multi-pole rod set. A segmented quadrupole rod set is particularly preferred. In the preferred embodiment ions are preferably introduced axially into the preferred ion guide or ion trap.

The preferred ion guide or ion trap is particularly advantageous compared to other known ion traps. According to the preferred embodiment the position of the axial potential well does not need to be modulated but rather the axial potential well is preferably static (in contrast to the first arrangement which is described for illustrative purposes).

Ions are preferably introduced into the preferred ion guide or ion trap orthogonally to the AC or RF voltage applied to the electrodes of the ion guide or ion trap and which acts to confine ions radially within the ion guide or ion trap. This is in contrast to conventional 3D or Paul ion traps.

According to a preferred embodiment ions are trapped both axially and radially within the preferred ion guide or ion trap. The ions may then be cooled to thermal energies within the preferred ion guide or ion trap by the introduction of collision gas into the preferred ion guide or ion trap. Ions may therefore be thermalised within the preferred ion guide or ion trap prior to mass-selective axial non-resonant ion ejection according to the preferred embodiment.

The preferred ion guide or ion trap preferably has substantially no physical restriction on the size of the device in the axial direction. This allows a much larger potential ion trapping capacity to be achieved compared to, for example, conventional 3D or Paul ion traps.

According to other embodiments a higher order multipole rod set or an ion tunnel or ion funnel ion guide or ion trap may be used.

According to the preferred embodiment an excitation waveform of an appropriate frequency and magnitude may be additionally applied along the axial ion trapping region of the preferred ion guide or ion trap.

Further less preferred embodiments are contemplated wherein the mode of ion ejection according to the first arrangement may be used in conjunction with the mode of ion ejection according to the preferred embodiment.

The preferred ion guide or ion trap has a number of important advantages over other known ion traps and particularly the ion trap disclosed in US-5783824 (Hitachi). One advantage is that the axial potential well maintained along the preferred ion guide or ion trap does not need to be quadratic in contrast to the arrangement disclosed in US-5783824. This highlights the fact that ion ejection from the preferred ion guide or ion trap is due to non-resonant ejection.

The preferred ion guide or ion trap has the further advantage that in a further mode of operation the axial DC potential may be removed thereby enabling the preferred ion guide or ion trap to be used as a conventional ion guide, ion trap, mass filter or mass analyser in the further mode of operation.

There is no restriction on the form of the axial potential which can be used according to the preferred embodiment and indeed many different potential profiles may be used including potential profiles having multiple axial ion trapping regions.

The preferred ion guide or ion trap is capable of operating effectively even when the potential well maintained along the axis of the preferred ion guide or ion trap suffers from imperfections or distortions due, for example, to the necessity of having a number of discrete electrodes each maintained at different voltages. It will be appreciated that maintaining a truly continuous smooth axial potential profile is difficult if not impossible to achieve in practice. An important advantage of the preferred embodiment therefore is that the performance of the preferred ion guide or ion trap is not affected if a substantially irregular or non continuous axial potential well is maintained along the length of the preferred ion guide or ion trap.

Various embodiments of the present invention together with other arrangements given for illustrative purposes only will now be described, by way of example only, and with reference to the accompanying drawings in which:

Fig. 1 shows a cross sectional view of a preferred segmented rod set ion guide or ion trap according to an embodiment;

Fig. 2 shows a side view of a preferred segmented ion guide or ion trap together with a plot showing the DC or electrostatic potentials applied to each segment of the preferred ion guide or trap according to the first illustrative arrangement so as to form a quadratic potential well along a portion of the ion guide or ion trap;

Fig. 3 shows the DC or electrostatic potentials applied to each segment of a preferred segmented ion guide or ion trap wherein the applied DC or electrostatic potentials are arranged to compensate for field relaxation effects at the boundaries of the axial ion trapping region of the ion guide or ion trap;

Fig. 4 shows the DC or electrostatic potentials applied to each segment of a preferred segmented ion guide or ion trap wherein the applied DC or electrostatic potentials are arranged so as to cause ions once they have exited the central axial ion trapping region to then be accelerated out of the ion guide or ion trap;

Fig. 5 shows the axial DC potential profile maintained over the axial ion trapping region of an ion guide or ion trap at three different times according to a first illustrative arrangement wherein the position of an axial quadratic potential well is modulated;

Fig. 6 shows the axial electric field maintained along the axial ion trapping region of an ion guide or ion trap at the three different times for the first illustrative arrangement described in relation to Fig. 5;

Fig. 7 shows an example of the axial DC potential profile maintained along an ion guide or ion trap according to the first illustrative arrangement at three different times wherein the position of the quadratic axial potential well is modulated;

Fig. 8A shows the amplitude of ion oscillation for ions having a mass to charge ratio of 200 along the axis of an ion guide or ion trap, Fig. 8B shows the amplitude of ion oscillation for ions having a mass to charge ratio of 300 along the axis of an ion guide or ion trap and Fig. 8C shows the amplitude of ion oscillation for ions having a mass to charge ratio of 400 along the axis of an ion guide or ion trap;

Fig. 9A shows a plot of the calculated amplitude of ion motion along the axis of an ion guide or ion trap versus time for ions having a mass to charge ratio of 200 when scanning the amplitude of displacement of the minimum of an axial potential well at a fixed modulation frequency, Fig. 9B shows a plot of the calculated amplitude of ion motion along the axis of an ion guide or ion trap versus time for ions having a mass to charge ratio of 300 when scanning the amplitude of displacement of the minimum of an axial potential well at a fixed modulation frequency and Fig. 9C shows a plot of the calculated amplitude of ion motion along the axis of an ion guide or ion trap versus time for ions having a mass to charge ratio of 400 when scanning the amplitude of displacement of the minimum of an axial potential well at a fixed modulation frequency;

Fig. 10 shows how the amplitude of axial displacement of the minimum of an axial quadratic potential well may be scanned as a function of time according to the first illustrative arrangement; and

Fig. 11 shows a simplified normalised stability diagram for an ion guide or ion trap.

Various embodiments of the present invention will be described in conjunction with describing a first illustrative arrangement which is not intended to fall within the scope of the present invention. According to the preferred embodiment an ion guide or ion trap is provided preferably comprising a segmented quadrupole rod set having hyperbolic shaped electrodes arranged as shown in Fig. 1. Each rod forming part of the overall quadrupole rod set assembly is preferably divided into a plurality of axial segments as shown in Fig. 2.

The preferred ion guide or ion trap preferably comprises a sufficient number of axial segments so as to allow DC or electrostatic potentials applied to each of the various segments to relax to a desired function.

Fig. 1 shows a cross-sectional view of a preferred ion guide or ion trap which preferably comprises a first pair of hyperbolic shaped electrodes or rods 1a,1b and a second pair of hyperbolic shaped electrodes or rods 2a,2b. Each electrode or rod 1a,1b,2a,2b is preferably axially segmented as shown in Fig. 2.

In operation an AC or RF voltage is preferably applied to each of the electrodes forming the preferred ion guide or ion trap so as to create a radial pseudo-potential well. The pseudo-potential well acts to confine ions radially (i.e. in the x,y plane) within the preferred ion guide or trap.

The AC or RF voltage applied to the electrodes forming the first pair of rods 1a,1b is preferably of the form:

$$\phi_1 = \phi_o \cos(\Omega_0 .t) \qquad (1)$$

wherein ϕ_o is half of the peak-to-peak voltage of the AC or RF high voltage power supply, t is the time in seconds and Ω_0 is the angular frequency of the AC or RF voltage supply in radians/second.

The AC or RF voltage applied to the electrodes forming the second pair of rods 2a,2b is preferably of the form:

$$\phi_2 = -\phi_o \cos(\Omega_0 .t) \qquad (2)$$

The potential in the x,y direction is therefore:

$$\phi_{x,y} = \phi_o \cos(\Omega_0 .t)\frac{(x^2 - y^2)}{2.r_o^{\,2}} \qquad (3)$$

wherein r_o is the radius of a circle inscribed by the two pairs of rods 1a,1b;2a,2b.

Ion motion in the x,y plane may be expressed using Mathieu's equation. The ion motion can be considered as comprising a low amplitude micro-motion with a frequency related to the AC or RF drive frequency superimposed upon a larger secular motion with a frequency related to the mass to charge ratio of the ion. The properties of Mathieu's equation are well known and solutions resulting in stable ion motion may be represented using a stability diagram by plotting the stability boundary conditions for the dimensionless parameters a_u and q_u as will be readily understood by those skilled in the art.

For the embodiment described above the parameters a_u and q_u are:

$$a_u = a_x = -a_y = \frac{8qU_0}{m\Omega_0{}^2 r_0{}^2} \qquad (4)$$

$$q_u = q_x = -q_y = \frac{4q\phi_0}{m\Omega_0{}^2 r_0{}^2} \qquad (5)$$

wherein m is the molecular mass of the ion, U_0 is a DC voltage applied to one of the pairs of rods, and q is the electron charge e multiplied by the number of charges on the ions.

The operation of a conventional quadrupole device for mass analysis is well known. The time-averaged effect due to the application of an AC or RF voltage to the electrodes results in the formation of a pseudo-potential well in the radial direction. An approximation of the pseudo-potential well in the x-direction may be given by:

$$V^*{}_{(x)} = \frac{q.\phi_0{}^2.x^2}{4.\Omega_0.m.r_0{}^4} \qquad (6)$$

The depth of the potential well for values of $q_x < 0.4$ is approximately:

$$\overline{D}_x = \frac{q_x \cdot \phi_0}{8} \quad (7)$$

As the quadrupole is cylindrically symmetrical an identical expression may be derived for the characteristics of the pseudo-potential well in the y-direction.

In addition to the pseudo-potential well which confines ions in the radial direction, an axial DC potential well or profile is also preferably maintained along at least a portion of the length of the preferred ion guide or ion trap.

According to the first illustrative arrangement the axial DC potential well is quadratic although importantly according to the preferred embodiment of the present invention the axial DC potential well does not need to be quadratic.

For the following illustration a quadratic potential well will be assumed. According to the first illustrative arrangement the quadratic potential well preferably has a minimum preferably located initially at the centre or middle of the ion guide or ion trap. If the potential well is quadratic then the axial DC potential will increase as the square of the distance or displacement away from the centre or middle of the ion guide or ion trap (or the minimum of the axial potential well).

For ease of illustration only a first illustrative arrangement will be considered wherein a quadratic potential well is provided and wherein the position of the quadratic potential well is modulated. From the discussion of this first illustrative arrangement the general principles of operation of an ion guide or ion trap according to the preferred embodiment will become apparent. The preferred embodiment differs from the first illustrative arrangement in that rather than providing a quadratic potential well and modulating the position of the quadratic potential well, according to the preferred embodiment a static potential well is provided which may or may not be quadratic and a time varying homogeneous axial electric field is applied additionally across the region of the static axial potential well.

According to the first illustrative arrangement the position of the axial quadratic DC potential well is altered or modulated with time in such a way that the minimum of the axial quadratic DC potential well is caused to oscillate in the axial or z-direction. The axial DC or electrostatic potential profile is therefore modulated in the axial direction as will be described in more detail with reference to Fig. 5. According to this arrangement the minimum of the quadratic DC or electrostatic axial potential well oscillates about the centre or middle of the ion guide or ion trap.

According to the first arrangement a time varying DC or electrostatic potential is maintained along the length of the ion guide or ion trap and is preferably of the form:

$$U_z(t) = \frac{k.[z + a.\cos(\Omega t)]^2}{2} \tag{8}$$

wherein k is the field constant of the axial DC quadratic potential, a is the axial distance along the ion guide or ion trap by which the minimum of the quadratic potential is moved about its mean position and Ω is the frequency of the modulation of the axial quadratic DC potential.

For illustrative purposes only an ion guide or ion trap as shown in Fig. 2 will now be considered. The ion guide or ion trap shown in Fig. 2 comprises 41 axial segments. The centremost or middle segment is shown labelled as segment number 0, with other segments being labelled 1 to 20 and -1 to -20 respectively. The ion guide or ion trap may be considered as having an overall axial length of 2T and an axial ion trapping region having a length 2L.

Reference is also made to the DC axial potential profile shown in Fig. 2 which is initially maintained along the length of the ion guide or ion trap according to this illustrative arrangement. The DC potential maintained along the ion guide or ion trap increases in proportion to the square of the distance or displacement from the central or middle segment until segment numbers ± 14. Segment numbers ± 14 are located at distances ± L from the minimum of the DC potential well (and the centre of the preferred ion guide or ion trap). At distances greater than ± L the DC potentials applied to the various segments of the ion guide or ion trap are preferably constant. Accordingly, ions which escape from the axial DC quadratic potential well and hence which are displaced at a distance greater than ± L will experience a substantially field free region. These ions will therefore be free to continue to move towards the entrance or exit of the ion guide or ion trap and will then exit the ion guide or ion trap.

The DC potentials applied to segments -15 to -20 and segments 15 to 20 of the ion guide or ion trap remain substantially constant as a function of time whereas the potentials applied to segments -14 to 14 change as a function of time. The distances ± L therefore define boundaries to an axial ion trapping region within the ion guide or ion trap. Ions which succeed in escaping the confines of the axial quadratic potential well or the axial ion trapping region are no longer axially confined within the ion guide or ion trap and are free to exit the ion guide or ion trap.

Due to field relaxation at the boundaries of the axial ion trapping region at distances ± L, the potential distribution within the axial ion trapping region of the ion guide or ion trap may not be exactly quadratic as desired according to the first illustrative arrangement.

In order to address the problem of field relaxation, the DC or electrostatic potentials applied to the electrodes at or around the boundaries of the axial ion trapping region may be modified to correct for distortions. Fig. 3 shows a plot of the DC potentials of each segment of an ion guide or ion trap according to an arrangement which is intended to address the problem of field relaxation at the boundary to the axial ion trapping region. The DC potentials of each segment of the ion guide or ion trap are substantially the same as those shown with reference Fig. 2 except that the potentials of segments ± 15 to 17 is higher than the potentials of segments ± 18 to 20. The DC potentials of segments ± 15 to 20 remain substantially constant as a function of time although it is contemplated that these potentials could vary with time.

The arrangement shown and described above with reference to Fig. 3 is advantageous in that the effect of field relaxation and field penetration at the boundaries of the axial ion trapping region may be substantially alleviated thereby leading to a more accurate, smooth or continuous axial quadratic potential profile being maintained within the axial ion trapping region of the ion guide or ion trap.

Fig. 4 shows a plot of the DC potentials of each segment of an ion guide or ion trap according to another arrangement wherein once ions have succeeded in escaping from the axial ion trapping region then they are accelerated out of the ion guide or ion trap. According to this arrangement the potential of segments ± 15 to 20 progressively decreases. The DC potentials of all the segments ± 15 to 20 preferably remain substantially constant as a function of time although it is contemplated that these potentials could vary with time.

Fig. 5 illustrates the general principles of how ions may be non-resonantly ejected from an ion guide or ion trap according to the first illustrative arrangement by modulating the position an axial quadratic potential well. Fig. 5 shows the DC or electrostatic axial potential profile as maintained along the trapping region of an ion guide or ion trap at three different times t1, t2 and t3. The boundaries of the central axial ion trapping region are indicated by axial positions ± L. It is to be noted that only potentials as shown within the region -L to L are actually applied to the electrodes of the ion guide or ion trap. The potentials shown by dashed lines at distances less than -L and greater than L are not actually applied to the electrodes of the ion guide or ion trap.

The axial potential profile at a first time t1 as shown in Fig. 5 corresponds with an axial quadratic DC potential well being maintained along an ion guide or ion trap wherein the minimum of the quadratic potential well is located at the centre or middle of the ion guide or ion trap. The DC potentials of the segments of the ion guide or ion trap corresponding to the axial ion trapping region are continually varied with time so that the minimum of the DC quadratic axial potential well is translated in a first direction with time. The minimum of the DC quadratic potential well is translated along the axis of the ion guide or ion trap until the minimum of the DC quadratic potential well reaches a maximum positive displacement of +a at a subsequent time t2 as shown in Fig. 5. The potentials of the segments of the ion guide or ion trap are then varied with time so that the minimum of the DC quadratic axial potential well is then translated back in a second opposed direction along the axis of the ion guide or ion trap until the minimum of the DC potential well reaches a maximum negative displacement of -a at a yet later time t3 as also shown in Fig. 5.

The position of the DC axial quadratic potential well is continuously varied or modulated in the manner as described above such that the minimum of the DC axial potential well is caused to oscillate about a predetermined position which is preferably the centre or middle of the ion guide or ion trap.

According to the arrangement discussed above with reference to Fig. 5 only the potentials of the axial segments located between the boundaries ±L defining the central axial ion trapping region are modulated in this manner. The potentials of the electrodes beyond the boundaries of the central axial ion trapping region located at ±L remain substantially constant with time.

The electric field E_z maintained across the central axial ion trapping region in the axial or z-direction is given by:

$$E_z(t) = \frac{\delta U_z}{\delta z} = k.\left[z + a\cos(\Omega.t)\right] \qquad (9)$$

Fig. 6 shows the axial electric field as maintained across the central axial ion trapping region of the ion guide or ion trap (and as described by Equation 9 above) at times t1, t2 and t3.

The axial electric field indicated by t1 in Fig. 6 represents the axial electric field maintained across the central axial ion trapping region at a time t1 when the minimum of the quadratic potential well is located at the centre or middle of the axial ion trapping region or the ion guide or ion trap. The axial electric field indicated by t2 in Fig. 6

represents the axial electric field maintained across the central axial ion trapping region at a time t2 when the minimum of the quadratic potential well is located at the position +a (i.e. beyond the axial ion trapping region). The axial electric field indicated by t3 in Fig. 6 represents the axial electric field maintained across the central axial ion trapping region at a time t3 when the minimum of the quadratic potential well is located at the position -a (i.e. also beyond the central axial ion trapping region). Accordingly, it is apparent from Fig. 6 that a linear axial electric field is provided across the central axial ion trapping region which can be considered as having an offset which changes with time.

Fig. 7 shows a graph of the axial DC potential profile maintained along an ion guide or ion trap at times t1, t2 or t3 during modulation of the minimum of an axial quadratic DC potential well according to a specific example. In this example the axial potential is maintained constant beyond the central axial ion trapping region defined by boundaries located at an axial distance of ± L. The boundary of the axial trapping potential ± L was set at ± 29 mm and the maximum displacement ± a of the minimum of the axial quadratic DC potential well was set at ± 203 mm (i.e. well outside the central axial ion trapping region).

The curve indicated as t1 in Fig. 7 represents the axial DC potential profile maintained along the ion guide or ion trap at time t1 when the minimum of the quadratic DC axial potential well is located at the centre or middle of the central axial ion trapping region. The curve indicated as t2 represents the potential profile maintained along the ion guide or ion trap at a subsequent time t2 when the minimum of the quadratic DC axial potential well is located at a position +a. The curve indicated as t3 represents the potential profile maintained along the ion guide or ion trap at a yet later time t3 when the minimum of the quadratic DC axial potential well is located at a position -a.

The force F_z on an ion in the z-direction within the central axial ion trapping region is given by:

$$F_z(t) = -q.E_z(t) = -q.k.[z + a\cos(\Omega.t)] \qquad (10)$$

The acceleration A_z of an ion within the central axial ion trapping region along the axial direction or z-axis is given by:

$$A_z = \ddot{z} = -\frac{q}{m}.k.[z + a\cos(\Omega.t)] \qquad (11)$$

The equation of motion of an ion in the axial direction within the central axial ion trapping region is given by:

$$\ddot{z} + \frac{q}{m}.k.z = -\frac{q}{m}.k.a\cos(\Omega.t) \qquad (12)$$

As will be appreciated by those skilled in the art, this equation of motion describes a forced linear harmonic oscillator. The exact solution is:

$$z(t) = z_1\cos(\omega.t) + \sqrt{(2.V/k)}.\sin(\omega.t) + \frac{q.k.a}{m(\omega^2 - \Omega^2)}[\cos(\Omega.t) - \cos(\omega.t)] \qquad (13)$$

wherein z_1 is the initial z coordinate of an ion at t=0, V is the initial kinetic energy of the ion in the z-direction at t= 0, $\omega = \sqrt{q.k/m}$ and is the fundamental frequency of simple harmonic motion of the ion, a is the amplitude of the modulation of the quadratic potential well in the axial z-direction and Ω is the frequency of the modulation of the axial quadratic potential well.

This solution considers that the amplitude of the modulation of the DC axial quadratic potential well is at a maximum at t=0. Different solutions may be found if the modulation of the axial field is started at differing phase angles. Equation 13 can be rewritten as:

$$z(t) = z_1\cos(\omega.t) + \sqrt{(2.V/k)}.\sin(\omega.t) - \frac{2.q.k.a}{m(\omega^2 - \Omega^2)}.\sin(\varpi_1.t).\sin(\varpi_2.t) \qquad (14)$$

wherein:

$$\varpi_1 = \frac{\Omega + \omega}{2}$$

$$\varpi_2 = \frac{\Omega - \omega}{2}$$

From Equation 14 it can be seen that ions trapped within the central axial ion trapping region will oscillate with a combination of frequencies which are independent of the initial kinetic energy V and starting position z1 of the ions. These frequencies are the fundamental harmonic frequency ω, and frequencies ϖ_1 and ϖ_2 as defined above.

Figs. 8A-8C show plots of the amplitude of ion oscillations in the axial direction for ions having mass to charge ratios of 200, 300 and 400 respectively. The position of the DC axial quadratic potential well is modulated as described above in relation to the specific example described with reference to Fig. 7.

The motion of ions is governed by Equation 13 derived above. For this particular example the field constant k for the quadratic axial DC potential well was set to 2378 V/m^2. The maximum axial displacement ± a of the minimum of the quadratic potential well was set to ± 202 mm. The quadratic axial DC potential well was modelled as being oscillated or modulated at a frequency Ω of 1.4×10^5 radians per second (22.3 kHz). The ions were modelled as starting from an initial position z1 equal to 0 mm and possessing an initial energy V equal to 0 eV.

It can be seen from Figs. 8A-8C that ions having a lower mass to charge ratio (see e.g. Fig. 8A which relates to ions having a mass to charge ratio of 200) have a corresponding higher amplitude of oscillation compared to ions having a lower mass to charge ratio (see e.g. Fig. 8C which relates to ions having a mass to charge ratio of 400). It can also be seen from Figs. 8A-8C that relative high frequency motion at frequencies ϖ_1 and ϖ_2 due to high frequency modulation of the DC axial quadratic potential well is superimposed upon a characteristically lower frequency simple harmonic motion occurring at the resonance frequency ω.

The equation of motion represented by Equation 12 above considers the motion of an ion wherein the maximum axial displacement ±a of the minimum of the axial quadratic potential well is fixed and wherein the frequency of modulation Ω of the axial quadratic potential well is also fixed. It is possible to consider the case where the frequency of modulation Ω of the axial quadratic DC potential well is constant and is greater than the fundamental resonance frequency ω of the ions and wherein the maximum axial displacement (a) of the quadratic axial potential well is now progressively increased linearly with time. Under these conditions a new equation of motion can be formulated:

$$A_z = \ddot{z} = -\frac{q}{m}.k.[z + a.t\cos(\Omega.t)] \qquad (15)$$

The solution to this equation is given by:

$$z(t) = z_1\cos(\omega.t) + \left[\sqrt{(2.V/k} - \frac{2.q.k.a.\Omega^2}{m.\omega.(\omega^2-\Omega^2)^2}\right].\sin(\omega.t) + \frac{q.k.a.t}{m(\omega^2-\Omega^2)}.\cos(\Omega.t) + \frac{2.q.k.a.\Omega}{m.(\omega^2-\Omega^2)^2}.\sin(\Omega.t) \qquad (16)$$

Equation 16 therefore describes the motion of ions during an analytical scan in which the maximum axial displacement of the minimum of the axial quadratic potential well is progressively increased. According to an arrangement such an analytical scan can be performed over a time period of several milliseconds in order to non-resonantly eject ions from the preferred ion guide or ion trap. Such an arrangement will be described in more detail below.

Figs. 9A-9C show plots of the amplitude of oscillation of ions in the axial direction versus time for ions having mass to charge ratios of 200, 300 and 400 respectively according to the first illustrative arrangement wherein the maximum axial displacement of the minimum of the axial quadratic potential well is progressively linearly increased with time. The ion motion is governed by Equation 16 as discussed above. The field constant k for the quadratic axial potential was set to 2378 V/m^2. The maximum axial displacement ± a of the minimum of the axial quadratic potential well was scanned or progressively increased from 0 to 400 mm over a time period of 8 ms. The frequency of modulation of the quadratic potential well was fixed at a frequency Ω of 1×10^5 radians per second (16 kHz). The ions were modelled as starting at an initial position z1 equal to 0.1 mm with an initial energy V equal to 0 eV.

It can be seen from comparing Figs. 9A-9C that as the maximum axial displacement of the minimum of the axial quadratic potential well progressively increases with time then so the maximum amplitude of oscillations of the ions in the axial direction also correspondingly increases. It is also apparent from comparing Figs. 9A-9C that ions having a relatively low mass to charge ratio (see e.g. Fig. 9A which relates to ions having a mass to charge ratio of 200) have a higher amplitude of oscillation than ions having a relatively high mass to charge ratio (see e.g. Fig. 9C which relates to ions having a mass to charge ratio of 400) for the same maximum axial displacement of the minimum of the axial quadratic potential well. Accordingly, ions having a relatively low mass to charge ratio will be ejected from the central axial ion trapping region of the ion guide or ion trap before ions having relatively higher mass to charge ratio.

Fig. 10 shows a plot of the scan function used in the arrangement described above with reference to Figs. 9A-9C in order to non-resonantly eject ions from the ion guide or ion trap. The y-axis shows the maximum axial displacement of the minimum of the DC axial quadratic potential well and the x-axis shows the time. In this particular arrangement the maximum axial displacement of the minimum of the DC axial quadratic potential well was progressively increased linearly with time from 0 mm to 400 mm over a period of 8 ms.

It will be understood by those skilled in the art that the application of an axial DC electrostatic voltage will also result in a radial electrostatic potential being generated within the ion guide or ion trap. To illustrate this ~~effect~~ an ion a segmented cylinder may be considered. Considering a quadratic potential of the form:

$$U_z(t) = \frac{k[z + a\cos(\Omega t)]^2}{2} \tag{17}$$

which is superimposed along the axis of the cylinder, then the potential in x,y,z is given by:

$$U_{z,x,y}(t) = k\left([z + a\cos(\Omega t)]^2 - \frac{(x^2 + y^2)}{2} + \frac{r_0^{\,2}}{2}\right) \tag{18}$$

wherein r_0 is the radius of the cylinder.

Equation 18 satisfies the Laplace condition given by:

$$\frac{\delta^2 z}{\delta x^2} + \frac{\delta^2 x}{\delta x^2} + \frac{\delta^2 y}{\delta y^2} = 0 \tag{19}$$

It can therefore be seen from Equation 18 that by superimposing an axially modulated quadratic DC potential along the axis of the cylinder, a static radial field is also produced which exerts a force on the ions in a direction away from the central axis of the cylinder towards the outer electrodes. However, provided that the radial pseudo-potential well created by the application of an AC or RF voltage to the outer electrodes is sufficient to overcome the radial force exerted on ions due to the axially modulated quadratic potential, then the ions will remain radially confined.

Although for ease of illustration a first illustrative arrangement has been described and discussed wherein the position of a quadratic potential well is modulated, the preferred embodiment of the present invention relates to an analogous but slightly different arrangement wherein a static axial potential well is maintained along the length of an ion trapping region of the ion guide or ion trap and a supplementary homogeneous time varying electric field is applied. An important aspect of the preferred embodiment is that a substantially equivalent set of equations to those detailed above in relation to the first illustrative arrangement can be generated for both the axial and radial fields by imposing, for example, a static axial DC potential of the form:

$$U_z = \frac{k.z^2}{2} \tag{20}$$

A supplementary time varying linear axial potential is preferably superimposed of the form:

$$V_z = c.z\cos(\Omega.t) \tag{21}$$

wherein c is a field strength constant equivalent to the field strength constant ka in equation 9, and Ω is the frequency of oscillation of the linear axial potential.

Ions will only be axially contained or confined within the ion trapping region of the preferred ion guide or ion trap when the amplitude of oscillations of the ions is such so that the ions remain within the boundaries ± L of the central axial ion trapping region of the preferred ion guide or ion trap. This condition may be used to define conditions of stable ion trapping within the preferred ion guide or ion trap. If an additional linear axial DC potential DC_z is applied across the axial ion trapping region according to either the first illustrative arrangement or according to the preferred embodiment of the form:

$$DC_z = b.z \tag{22}$$

then the position of the minimum of the axial potential well will be displaced thereby altering the amplitude of oscillation at which ions will become unstable. This method can therefore also be used to progressively scan ions out of the preferred ion guide or ion trap.

A stability diagram for the preferred ion guide or ion trap may be generated in terms of the variables a, b, k, m, Ω and L wherein L is the distance from the minimum of an axial quadratic potential well to each boundary of the central axial ion trapping region.

Fig. 11 shows the stability diagram for the preferred ion guide or ion trap with regions of stability and instability indicated. The y-axis represents the normalised magnitude of the axial displacement of the minimum of the mean axial potential resulting from application of a static linear potential DC_z. The x-axis represents normalised amplitude of oscillation. The region of the stability diagram labelled Z Stable indicates that ions are stable and remain trapped within the ion guide or ion trap. The regions labelled Unstable indicate that ions do not remain trapped and leave the ion guide or ion trap. The region labelled +Z Unstable indicates that ions will leave the ion guide or ion trap from one end of the ion guide or ion trap. Similarly, the region labelled -Z Unstable indicates that ions will leave the ion guide or ion trap from the other end of the ion guide or ion trap. The region labelled ±Z Unstable indicates that ions will leave the ion guide or ion trap from both ends.

The stability diagram shown in Fig. 11 assumes that ions have first been subject to collisional cooling within the ion guide or ion trap such that the amplitude of their oscillations is predominantly governed by the amplitude of their high frequency motion which is due, for example, to modulation of the position of a quadratic potential well rather than by the amplitude of lower frequency harmonic motion within an axial electrostatic or DC quadratic potential well.

The expression for the normalised amplitude of oscillation can be modified to include different starting conditions including different initial energies V and different initial position terms z1 for the ions. The expression can also be modified to include the initial starting phase of the modulation of an axial quadratic potential well.

The motion of ions within the axial ion trapping region of the preferred ion guide or ion trap may be modified by the introduction of a collisional damping gas into the preferred ion guide or ion trap. The equation of motion in the presence of a damping gas is given as:

$$\ddot{z} + \lambda\dot{z} + \frac{q}{m}.k.z = \frac{q}{m}.k.a\cos(\Omega.t) \qquad (23)$$

wherein λ is the damping constant and is a function of the mobility of the ions.

Ion mobility is a function of the ion cross-sectional area, the damping gas number density, the ion charge, the masses of the ion and the gas molecules, and the temperature. Hence, in the presence of a damping gas the equation of motion will also be dependent upon the mobility of the ions. Accordingly, in these circumstances the conditions for stable and unstable ion motion will also be dependent upon the ion mobility. New equations of motion and stability diagrams can therefore be generated for different damping conditions and ions can be separated according to their ion mobility as well as according to their mass to charge ratio.

In the preferred embodiment the DC voltage applied to each individual segment of the preferred ion guide or ion trap is preferably generated using individual low voltage power supplies. The outputs of the DC power supplies are preferably controlled by a programmable microprocessor. The general form of the electrostatic potential function in the axial direction can preferably be rapidly manipulated and complex and/or time varying potentials can be superimposed along the axial direction of the preferred ion guide or ion trap.

In the preferred embodiment ions are preferably introduced into the preferred ion guide or ion trap from an external ion source either in a pulsed or a substantially continuous manner. During the introduction of a continuous beam of ions from an external ion source, the initial axial energy of the ions entering the preferred ion guide or ion trap may be preferably arranged such that all ions having mass to charge ratios within a desired range are preferably radially confined within the preferred ion guide or ion trap by the application of an AC or RF voltage to the electrodes. The ions may also become trapped axially by superimposing axial electrostatic potentials. The initial trapping DC or electrostatic potential function in the axial direction may or may not be quadratic and the minimum of the axial DC trapping potential may or may not correspond to the centre or middle of the preferred ion guide or ion trap. As ions are introduced into the preferred ion guide or ion trap the axial DC potential well is preferably static.

The initial trapping of ions within the preferred ion guide or ion trap may be accomplished in the absence of a cooling gas or alternatively it may be accomplished in the presence of a cooling gas.

Once the ions are confined within the axial ion trapping region of the preferred ion guide or ion trap their initial energy spread may be preferably reduced either by introducing a cooling gas into the ion confinement or axial ion trapping region or by the presence of cooling gas which is already present within the axial ion trapping region. The cooling gas may preferably be maintained at a pressure in the range of 10^{-4} to 10^{1} mbar, more preferably in the range of 10^{-3} to 10^{-1} mbar. The kinetic energy of the ions will be preferably lost in collisions with the cooling gas molecules and the ions will preferably reach thermal energies. Collisions with residual gas molecules will preferably eventually cause the amplitude of the oscillations of the ions to decrease and hence ions will tend to collapse towards the centre or minimum of the axial DC potential well. However, although ions will lose energy they will not be lost from the preferred ion guide or ion trap as they will remain confined by the radial pseudo-potential well. Accordingly, the preferred ion guide or ion trap is particularly advantageous compared to other ion traps such as orbitraps wherein ions will be lost to the system if they lose sufficient energy due to collisions with gas molecules. For this reason orbitraps have to be operated at an Ultra High Vacuum (UHV) which is disadvantageous.

According to the preferred embodiment, ions of differing mass to charge ratios are preferably made to migrate along the axis of the preferred ion guide or ion trap to the point of lowest electrostatic potential so that the spatial spread and energy range of the ions is preferably minimised.

According to an arrangement once the ions have been thermally cooled and are preferably located at the minimum of the axial potential well, the position of the axial potential well may then be modulated and the amplitude of oscillations may be increased. The frequency of the modulation of the axial potential well may be maintained above the fundamental resonance frequency of the ions.

According to an arrangement mass selective ejection of ions may be commenced in a non-resonant manner by progressively increasing the amplitude of the axial modulation of the minimum of the axial potential well whilst keeping the modulation frequency Ω constant.

According to an alternative arrangement, mass selective ejection of ions from the ion guide or ion trap may be achieved by keeping the amplitude of modulation of the axial potential well constant and by progressively decreasing the frequency Ω of the modulation of the axial potential well.

According to another arrangement, mass selective ejection from the preferred ion guide or ion trap may be achieved by varying both the amplitude of and the frequency Ω of the axial modulation of the axial potential well.

It is also contemplated that in a mode of operation both the frequency and the amplitude of the axial modulation of the axial potential well may be fixed and instead the mean position of the minimum of the axial potential well may be moved relative to the physical dimensions of the ion guide or ion trap. Ions having relatively low mass to charge ratios will have higher amplitudes of motion in the axial direction and hence will preferably be ejected from the ion guide or ion trap before ions having relatively high mass to charge ratios.

In another mode of operation the frequency and amplitude of the axial modulation of the axial potential well may also be fixed and the position of the minimum of the time averaged electrostatic potential may be fixed. According to this arrangement the field constant k of the axial electrostatic potential well is progressively lowered. In this arrangement ions having relatively low mass to charge ratios will be ejected from the ion guide or ion trap before ions having relatively high mass to change ratios.

In an arrangement the minimum of the axial potential well may be displaced from the centre of the preferred ion guide or ion trap so that ions are preferably ejected from one end only of the preferred ion guide or ion trap.

Ions which are ejected from the preferred ion guide or ion trap may be subsequently detected using an ion detector. The ion detector may comprise an ion detector such as a micro-channel plate (MCP) ion detector, a channeltron or discrete dynode electron multiplier or a conversion dynode detector. Phosphor or scintillator detectors and photo-multipliers may also be used. Alternatively, ions ejected from the preferred ion guide or ion trap may be onwardly transmitted to a collision gas cell or another component of a mass spectrometer. According to an embodiment ions ejected from the preferred ion guide or ion trap may be mass analysed by a mass analyser such as a Time of Flight mass analyser or a quadrupole mass analyser.

In addition to the mass selective instability modes of operation described above, according to other embodiments the preferred ion guide or ion trap may in a mode of operation also advantageously be operated in a known manner wherein, for example, ions are resonantly ejected axially from the preferred ion guide or ion trap.

According to an embodiment ions may be resonantly excited at their fundamental harmonic frequency but may not be excited sufficiently such that they exit the preferred ion guide or ion trap. Instead, ions may be caused to be ejected from the ion guide or ion trap due to the additional effect due to modulation of the axial potential well at a frequency substantially higher than the fundamental resonance frequency of the ions or by the method of non-resonant ion ejection according to the preferred embodiment.

According to an arrangement the amplitude of ion oscillation may be increased by increasing the amplitude of the axial modulation of the axial potential well or by decreasing the frequency of the axial modulation Ω of the potential well as described above. However, at a time before ions of a specific mass to charge ratio are actually ejected from the preferred ion guide or ion trap, a small amount of resonance excitation may be applied at a frequency corresponding to the fundamental resonance frequency ω of the ions desired to be ejected in order to increase their amplitude of oscillation. However, although the ions are partially excited in a resonant manner the ions are actually caused to be ejected from the ion guide or ion trap due to non-resonant excitation.

In addition to a MS mode of operation as described above the preferred ion guide or ion trap may also be used for MS^n experiments wherein ions are fragmented and the resulting daughter or fragment ions are then mass analysed. In the preferred embodiment wherein the preferred ion guide or ion trap comprises a segmented quadrupole rod set, parent or precursor ions of interest having a specific mass to charge ratio may be selected using the well-known radial stability characteristics of the RF quadrupole. In particular, application of a dipolar resonance voltage or a resolving DC voltage may be used to reject ions having a specific mass to charge ratio either as ions enter the quadrupole or once they have been initially trapped within the quadrupole rod set.

In another embodiment precursor or parent ions may be selected by axial resonance ejection from the axial potential well. In this case a broad band of excitation frequencies may be applied simultaneously to the electrodes forming the axial trapping system. All ions with the exception of the desired precursor or parent ion to be subsequently analysed are then preferably caused to be ejected from the preferred ion guide or ion trap. The method of inverse Fourier transform may be employed to generate the waveform suitable for resonance ejection of a broad range of ions whilst leaving ions having a specific desired mass to charge ratio within the preferred ion guide or ion trap.

In another embodiment precursor or parent ions may be selected using a combination of axial resonance ejection from the axial electrostatic potential well together with mass selective non-resonant ejection according to the preferred embodiment of the present invention.

Once desired precursor or parent ions have been isolated in the preferred ion guide or ion trap, collision gas may then be preferably introduced or reintroduced into the preferred ion guide or ion trap. Fragmentation of the selected precursor or parent ions may then be accomplished by increasing the amplitude of oscillation of the ions and therefore the velocity of the ions. This may be achieved by increasing the amplitude of oscillation of the axial potential well, decreasing the frequency Ω of axial modulation of the electrostatic potential or by superimposing an excitation waveform at a frequency corresponding to the harmonic frequency ω of the precursor or parent ions.

According to an alternative embodiment fragmentation may be accomplished by increasing the amplitude of oscillation of the precursor or parent ions and therefore the velocity of the ions in the radial direction. This may be achieved by altering the frequency or amplitude of the AC or RF voltage applied to the quadrupole rods or by superimposing a dipolar excitation waveform in the radial direction to one pair of quadrupole rods which has a frequency matching the secular frequency characteristic of the ions of interest. A combination of any of these techniques may be used to excite desired precursor or parent ions thereby causing them to possess sufficient energy such that they are then caused to fragment. The resulting fragment or daughter ions may then be mass analysed by any of the methods described above.

The process of selecting ions and exciting them may be repeated to allow MS^n experiments to be performed.
The resulting MS^n ions may then be axially ejected from the preferred ion guide or ion trap using the methods previously described.

According to other embodiments a monopole, hexapole, octapole or a higher order multi-pole ion guide or ion trap may be utilised for radial confinement of ions. Higher order multi-poles are particularly advantageous in that they have a higher order pseudo-potential well function. When a higher order multi-pole ion guide or ion trap is used in a resonance ejection mode of operation, the higher order fields within such non-quadrupolar devices reduce the likelihood of radial resonance losses. In non-linear radial fields the frequency of the radial secular motion is related to position of the ions and hence ions will go out of resonance before they are ejected. Furthermore, the base of the pseudo-potential well generated within a higher order multi-pole ion guide is broader than that of a quadrupole and hence non-quadrupolar devices potentially possess a higher capacity for charge. Therefore, such devices offer the possibility of improved overall dynamic range. The rods of multi-pole ion guides or ion traps according to embodiments of the present invention may have hyperbolic, circular, arcuate, rectangular or square cross-sections. Other cross-sectional shapes may also be used according to less preferred embodiments.

In an embodiment the superimposed axial DC voltage function may be linear or non-linear. It is also contemplated that non-linear voltage functions such as polynomial, exponential or more complex functions may be used.

According to the preferred embodiment a static axial DC potential is preferably maintained along the length of the axial ion trapping region of the preferred ion guide or ion trap.

A periodic function other than that described by cosine or sine functions may be utilised for voltage modulation. For example, voltages may be stepped between maximum values using digital programming.

According to another embodiment the ion guide or ion trap may comprise a continuous rod set rather than a segmented rod set. According to such an embodiment the rods may comprise a non-conducting material (e.g. a ceramic or other insulator) and may be coated with a non-uniform resistive material. The application of a voltage between, for example, the centre of the rods and the ends of the rods will result in an axial DC potential well being generated along the axial ion trapping region of the preferred ion guide or ion trap.

According to an embodiment a desired axial DC potential profile may be developed at each segment of the preferred ion guide or ion trap using a series of fixed or variable resistors between the individual segments or electrodes of the preferred ion guide or ion trap.

In another embodiment a desired axial DC potential profile may be provided by one or more auxiliary electrodes which may be arranged around or alongside the electrodes forming the preferred ion guide or ion trap. The one or more auxiliary electrodes may, for example, comprise a segmented electrode arrangement, one or more resistively coated electrodes, or other suitably shaped electrodes. Application of a suitable voltage or voltages to the one or more auxiliary electrodes preferably causes a desired axial DC potential profile to be maintained along the axial ion trapping region of the preferred ion guide or ion trap.

In an embodiment the preferred ion guide or ion trap may comprise an AC or RF ring stack arrangement comprising a plurality of electrodes having circular or non-circular apertures through which ions are transmitted in use. An ion tunnel arrangement may, for example, be used for radial confinement of the ions. In such an embodiment an AC or RF voltage of alternating polarity is preferably applied to adjacent annular rings of the ion tunnel device in order to generate a radial pseudo-potential well for radially confining the ions. An axial potential may be preferably superimposed along the length of ion tunnel ion guide or ion trap.

In another embodiment radial confinement of ions may be achieved using an ion guide comprising a stack of plates or planar electrodes wherein opposite phases of an AC or RF voltage are applied to adjacent plates or electrodes. Plates or electrodes at the top and bottom of such a stack of plates or electrodes may be supplied with a DC and/or RF trapping voltage so that an ion trapping volume is formed. The confining plates or electrodes may themselves be segmented thereby allowing an axial trapping electrostatic potential function to be superimposed along the length of the preferred ion guide or ion trap and so that mass selective axial ejection of ions may be performed using the methods according to the preferred embodiment.

According to an embodiment multiple axial DC potential wells may be maintained or formed along the length of the preferred ion guide or ion trap. By manipulating the superimposed DC potentials applied to the electrode segments, ions may be caused to be trapped in one or more specific axial ion trapping regions. Ions trapped within a DC potential well in a specific region of a preferred ion guide or ion trap may then, for example, be subjected to mass selective ejection causing one or more ions to leave that potential well. Those ions ejected from one potential well may then be subsequently trapped in a second or different potential well within the same preferred ion guide or ion trap. This type of operation may be utilised, for example, to study ion-ion interactions. In this mode of operation ions may be introduced from either or both ends of the preferred ion guide or ion trap substantially simultaneously.

According to an embodiment ions trapped in a first potential well may be subjected to a resonance ejection condition which preferably causes only ions having a certain mass to charge ratio or certain range of mass to charge ratios to be ejected from the first potential well. Ions ejected from the first potential well then preferably pass to a second potential well. Resonance excitation may then be performed in the second potential well in order to fragment these ions. The resulting daughter or fragment ions may then be sequentially resonantly ejected from the second potential well for subsequent axial detection. Repeating this process enables MS/MS analysis of all the ions within the first potential well to be performed or recorded with substantially 100% efficiency.

According to further embodiments more than two potential wells may be maintained along an axial ion trapping region within the preferred ion guide or ion trap thereby allowing increasingly complex experiments to be realised. Alternatively, this flexibility may be used to condition the characteristics of ion packets for introduction to other analysis techniques.

In the present application it is understood that conventionally ions are resonantly ejected by exciting the ions at the first or fundamental resonance frequency. However, it is also contemplated that according to a mode of operation ions may be resonantly excited or ejected from a preferred ion guide or ion trap by exciting the ions at second or higher order harmonics of the fundamental resonance frequency. The present invention is intended to cover embodiments wherein the time varying substantially homogeneous axial electric field is varied at frequencies which are greater than the first or fundamental resonance frequency or frequencies of the ions contained within the ion guide or ion trap. The frequency of modulation of the substantially homogeneous axial electric field may or may not correspond with a second or higher harmonic frequency or frequencies of the fundamental resonance frequency of the ions within the ion guide or ion trap.

Claims

1. An ion guide or ion trap comprising:

a plurality of electrodes;

AC or RF voltage means arranged and adapted to apply an AC or RF voltage to at least some of said plurality of electrodes in order to confine radially at least some ions within said ion guide or ion trap;

first means arranged and adapted to maintain one or more DC, real or static potential wells or a substantially static inhomogeneous electric field along at least a portion of the axial length of said ion guide or ion trap in a first mode of operation; and

second means arranged and adapted to maintain a time varying substantially homogeneous axial electric field along at least a portion of the axial length of said ion guide or ion trap in said first mode of operation;

wherein the electric field is varied with time so as to cause ions to oscillate axially along the ion guide or ion trap such that at least some ions are ejected from a trapping region of said ion guide or ion trap in a substantially non-resonant manner whilst other ions are arranged to remain substantially trapped within said trapping region of said ion guide or ion trap.

2. An ion guide or ion trap as claimed in claim 1, wherein said first means is arranged and adapted to maintain one or more substantially quadratic potential wells along at least a portion of the axial length of said ion guide or ion trap.

3. An ion guide or ion trap as claimed in claim 1 or 2, wherein said first means is arranged and adapted to maintain one or more potential wells along at least 20% of the axial length of said ion guide or ion trap.

4. An ion guide or ion trap as claimed in claim 1, 2 or 3, wherein said first means is arranged and adapted to provide an electric field having an electric field strength which varies or increases along at least 20% of the axial length of said ion guide or ion trap.

5. An ion guide or ion trap as claimed in any one of claims 1-4, wherein said second means is arranged and adapted to maintain said time varying homogeneous axial electric field along at least 20% of the axial length of said ion guide or ion trap.

6. An ion guide or ion trap as claimed in any one of claims 1-5, wherein said second means comprises one or more DC voltage supplies for supplying one or more DC voltages to at least 20% of said electrodes.

7. An ion guide or ion trap as claimed in any one of claims 1-6, wherein said second means is arranged and adapted in said first mode of operation to generate an axial electric field which has a substantially constant electric field strength along the axial length of said ion guide or ion trap at any point in time.

8. An ion guide or ion trap as claimed in any one of claims 1-7, wherein said second means is arranged and adapted in said first mode of operation to generate an axial electric field which has an electric field strength which varies by at least 10% with time.

9. An ion guide or ion trap as claimed in any one of claims 1-8, wherein said second means is arranged and adapted in said first mode of operation to generate an axial electric field which changes direction with time.

10. An ion guide or ion trap as claimed in any one of claims 1-9, wherein said second means is arranged and adapted to generate an axial electric field which has an offset which changes with time.

11. An ion guide or ion trap as claimed in any one of claims 1-10, wherein said second means is arranged and adapted to vary said time varying substantially homogeneous axial electric field with or at a first frequency f_1, wherein f_1 is selected from the group consisting of: (i) < 5 kHz; (ii) 5-10 kHz; (iii) 10-15 kHz; (iv) 15-20 kHz; (v) 20-25 kHz; (vi) 25-30 kHz; (vii) 30-35 kHz; (viii) 35-40 kHz; (ix) 40-45 kHz; (x) 45-50 kHz; (xi) 50-55 kHz; (xii) 55-60 kHz; (xiii) 60-65 kHz; (xiv) 65-70 kHz; (xv) 70-75 kHz; (xvi) 75-80 kHz; (xvii) 80-85 kHz; (xviii) 85-90 kHz; (xix) 90-95 kHz; (xx) 95-100 kHz; and (xxi) > 100 kHz.

12. An ion guide or ion trap as claimed in claim 11, wherein said first frequency f_1 is greater than the resonance or fundamental harmonic frequency of at least 10% of the ions located within an ion trapping region within said ion guide or ion trap.

13. An ion guide or ion trap as claimed in any one of claims 1-12, wherein said ejection means is arranged and adapted to vary the amplitude of said time varying substantially homogeneous axial electric field.

14. An ion guide or ion trap as claimed in any one of claims 1-13, wherein said ejection means is arranged and adapted to vary the frequency of oscillation or modulation of said time varying substantially homogeneous axial electric field.

15. An ion guide or ion trap as claimed in any one of claims 1-14, wherein said ejection means is arranged and adapted to mass selectively eject ions from said ion guide or ion trap.

16. An ion guide or ion trap as claimed in any one of claims 1-15, wherein said ejection means is arranged and adapted in said first mode of operation to eject ions substantially axially from said ion guide or ion trap.

17. An ion guide or ion trap as claimed in any one of claims 1-16, wherein ions are arranged to be trapped or axially confined within an ion trapping region within said ion guide or ion trap, said ion trapping region having a length l, wherein l is selected from the group consisting of: (i) < 20 mm; (ii) 20-40 mm; (iii) 40-60 mm; (iv) 60-80 mm; (v) 80-100 mm; (vi) 100-120 mm; (vii) 120-140 mm; (viii) 140-160 mm; (ix) 160-180 mm; (x) 180-200 mm; and (xi) > 200 mm.

18. An ion guide or ion trap as claimed in any one of claims 1-17, wherein said ion trap or ion guide comprises a linear ion trap or ion guide.

19. An ion guide or ion trap as claimed in any one of claims 1-18, wherein said ion guide or ion trap is segmented axially or comprises a plurality of axial segments.

20. An ion guide or ion trap as claimed in claim 19, wherein said ion guide or ion trap comprises x axial segments, wherein x is selected from the group consisting of: (i) < 10; (ii) 10-20; (iii) 20-30; (iv) 30-40; (v) 40-50; (vi) 50-60; (vii) 60-70; (viii) 70-80; (ix) 80-90; (x) 90-100; and (xi) > 100.

21. An ion guide or ion trap as claimed in any one of claims 1-20, wherein said ion guide or ion trap comprises a plurality of electrodes having apertures wherein ions are transmitted, in use, through said apertures.

22. An ion guide or ion trap as claimed in any one of claims 1-21, wherein in a mode of operation ions are trapped but are not substantially fragmented within said ion guide or ion trap.

23. An ion guide or ion trap as claimed in any one of claims 1-22, further comprising means arranged and adapted to collisionally cool or substantially thermalise ions within said ion guide or ion trap in a mode of operation.

24. An ion guide or ion trap as claimed in any one of claims 1-23, further comprising means arranged and adapted to store or trap ions within said ion guide or ion trap in a mode of operation at one or more positions which are closest to the entrance, centre or exit of said ion guide or ion trap.

25. An ion guide or ion trap as claimed in any one of claims 1-24, further comprising means arranged and adapted to trap ions within said ion guide or ion trap in a mode of operation and to progressively move said ions towards the entrance, centre or exit of said ion guide or ion trap.

26. An ion guide or ion trap as claimed in any one of claims 1-25, further comprising means arranged and adapted to apply one or more transient DC voltages or one or more transient DC voltage waveforms to said electrodes initially at a first axial position, wherein said one or more transient DC voltages or one or more transient DC voltage waveforms are then subsequently provided at second, then third different axial positions along said ion guide or ion trap.

27. An ion guide or ion trap as claimed in any one of claims 1-26, further comprising means arranged and adapted to apply, move or translate one or more transient DC voltages or one or more transient DC voltage waveforms from one end of said ion guide or ion trap to another end of said ion guide or ion trap in order to

urge ions along at least a portion of the axial length of said ion guide or ion trap.

28. A mass spectrometer comprising an ion guide or an ion trap as claimed in any one of claims 1-27.

29. A mass spectrometer as claimed in claim 28, further comprising one or more ion detectors arranged upstream or downstream of said ion guide or ion trap.

30. A method of guiding or trapping ions comprising:

providing an ion guide or ion trap comprising a plurality of electrodes;

applying an AC or RF voltage to at least some of said plurality of electrodes in order to confine radially at least some ions within said ion guide or ion trap;

maintaining one or more DC, real or static potential wells or a substantially static inhomogeneous electric field along at least a portion of the axial length of said ion guide or ion trap in a first mode of operation; and

maintaining a time varying substantially homogeneous axial electric field along at least a portion of the axial length of said ion guide or ion trap in said first mode of operation;

wherein the electric field is varied with time so as to cause ions to oscillate axially along the ion guide or ion trap such that at least some ions are ejected from a trapping region of said ion guide or ion trap in a substantially non-resonant manner whilst other ions are arranged to remain substantially trapped within said trapping region of said ion guide or ion trap.

31. A method of mass spectrometry comprising the method of guiding or trapping ions as claimed in claim 30.

32. An ion guide or ion trap comprising:

a plurality of electrodes;

first means arranged and adapted to maintain one or more DC, real or static potential wells or a substantially static inhomogeneous electric field along at least a portion of the axial length of said ion guide or ion trap in a first mode of operation; and

second means arranged and adapted to maintain a time varying substantially homogeneous axial electric field along at least a portion of the axial length of said ion guide or ion trap in said first mode of operation;

wherein the electric field is varied with time so as to cause ions to oscillate axially along the ion guide or ion trap such that at least some ions are ejected from a trapping region of said ion guide or ion trap in a substantially non-resonant manner whilst other ions are arranged to remain substantially trapped within said trapping region of said ion guide or ion trap.

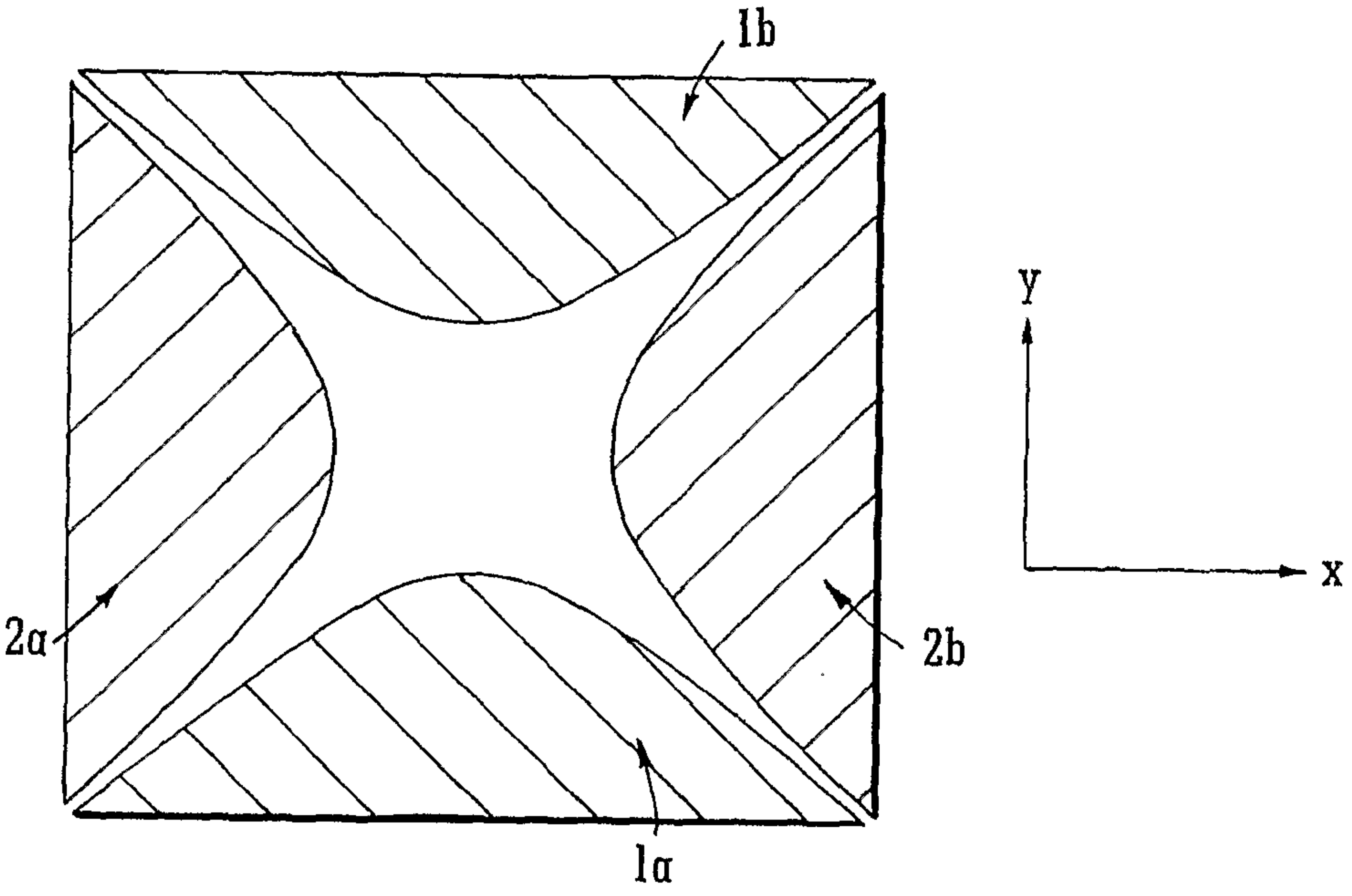
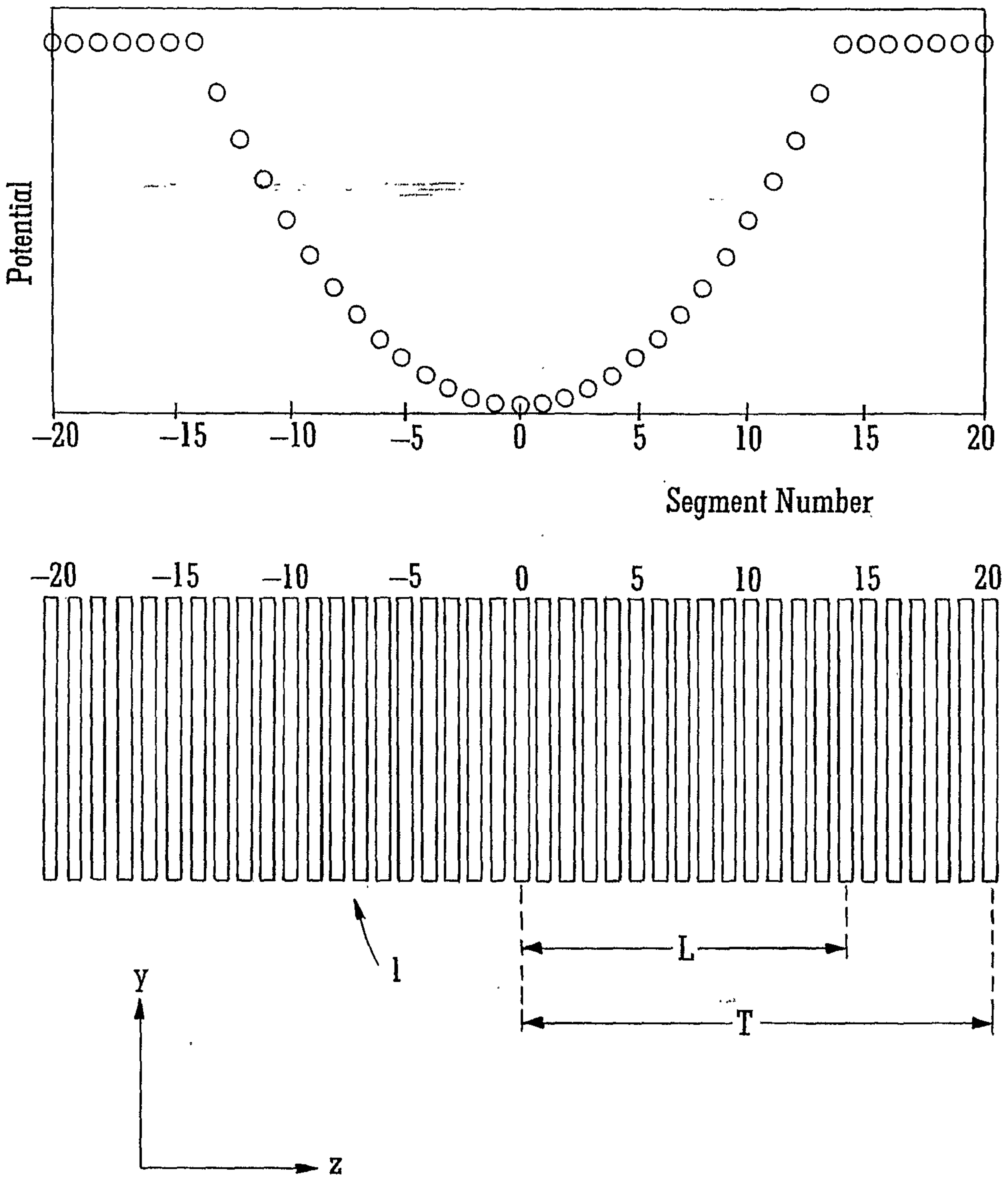


FIG. 1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−10
−5
0
5
10
15
20
Segment Number
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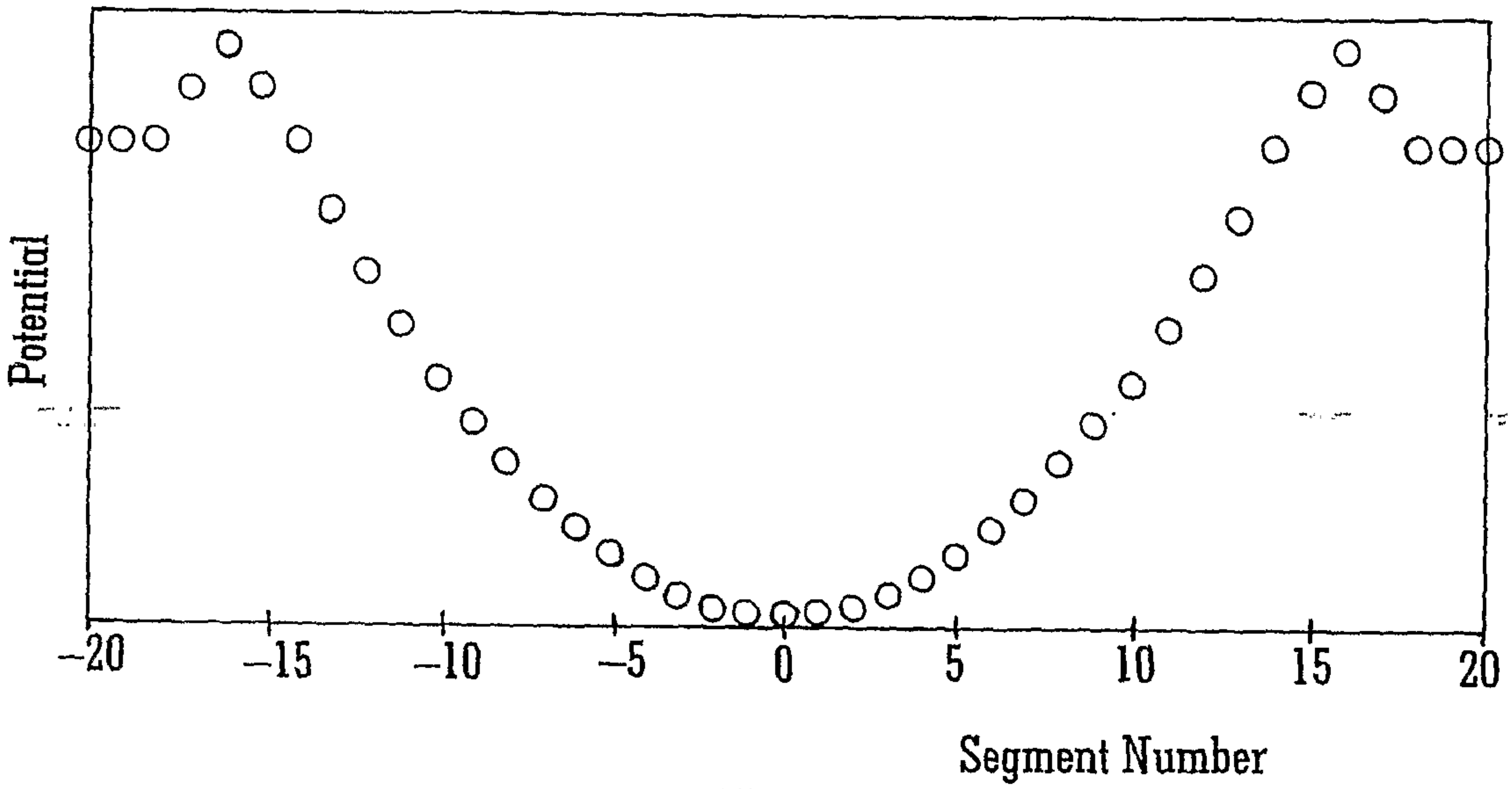
15
20
1
L
T
y
z

FIG. 2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-10
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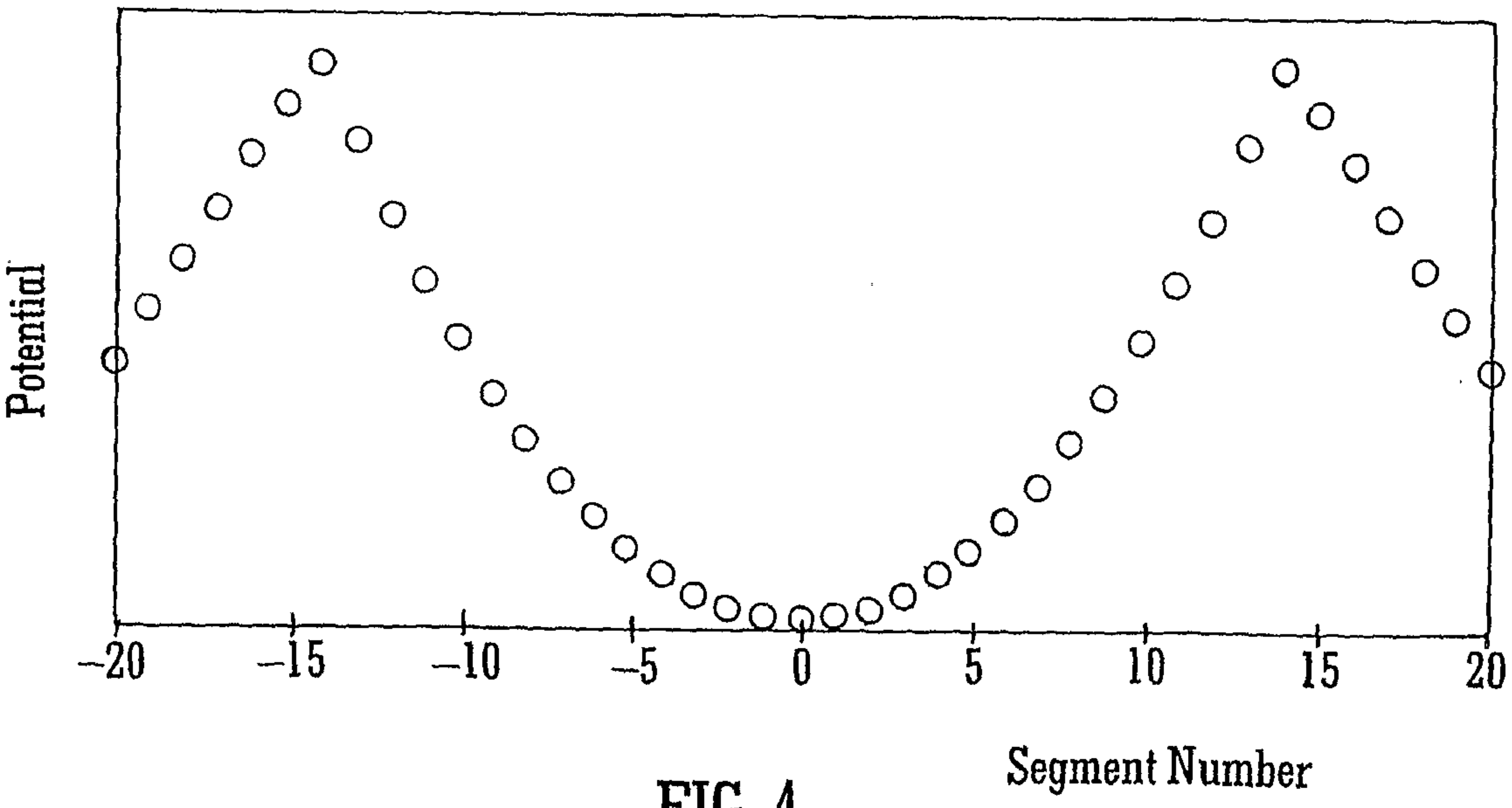
5
10
15
20
Segment Number

FIG. 3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5
10
15
20
Segment Number

FIG. 4

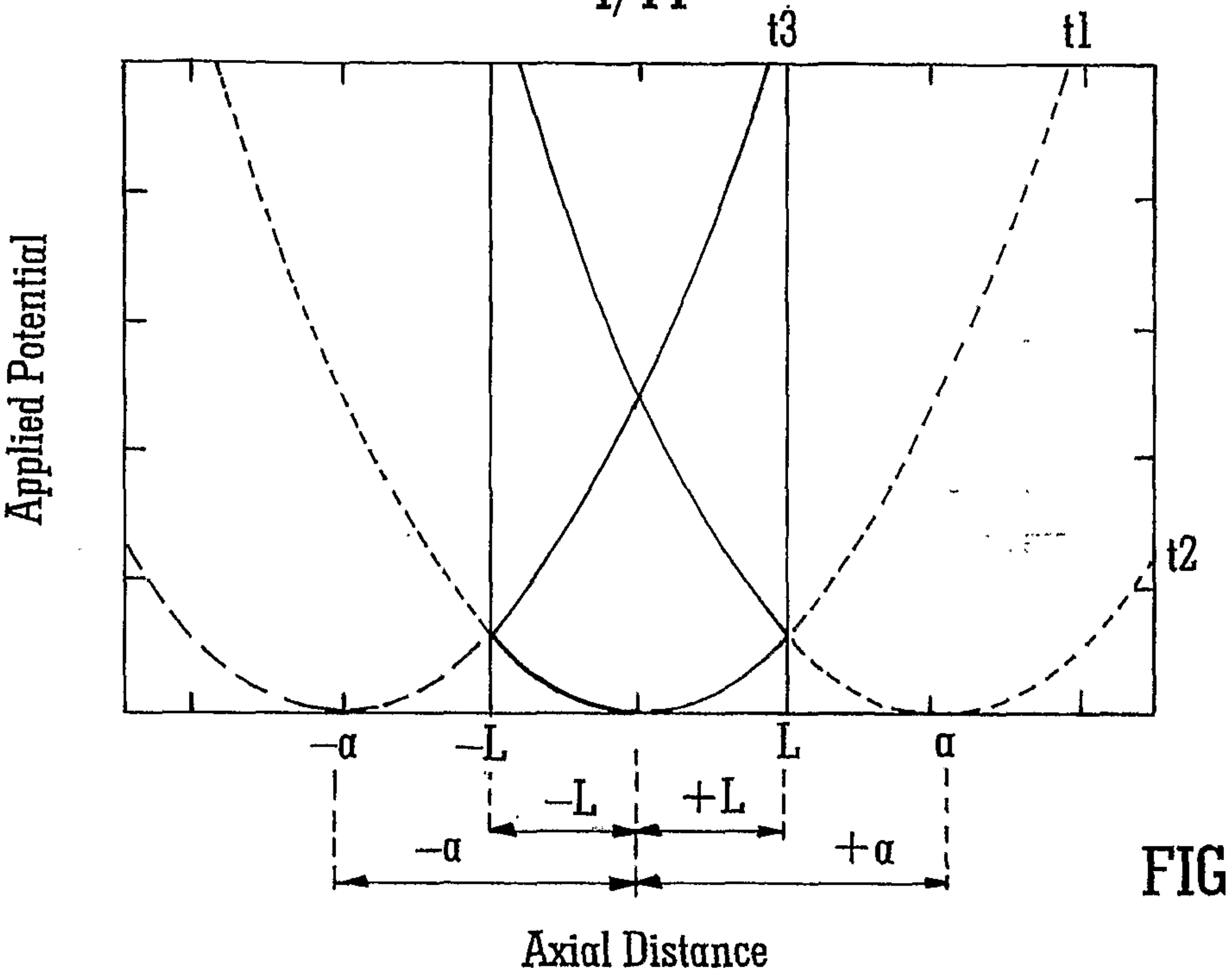

t3
t1
t2
Applied Potential
−a
−L
L
a
−L
+L
−a
+a
Axial Distance

FIG. 5

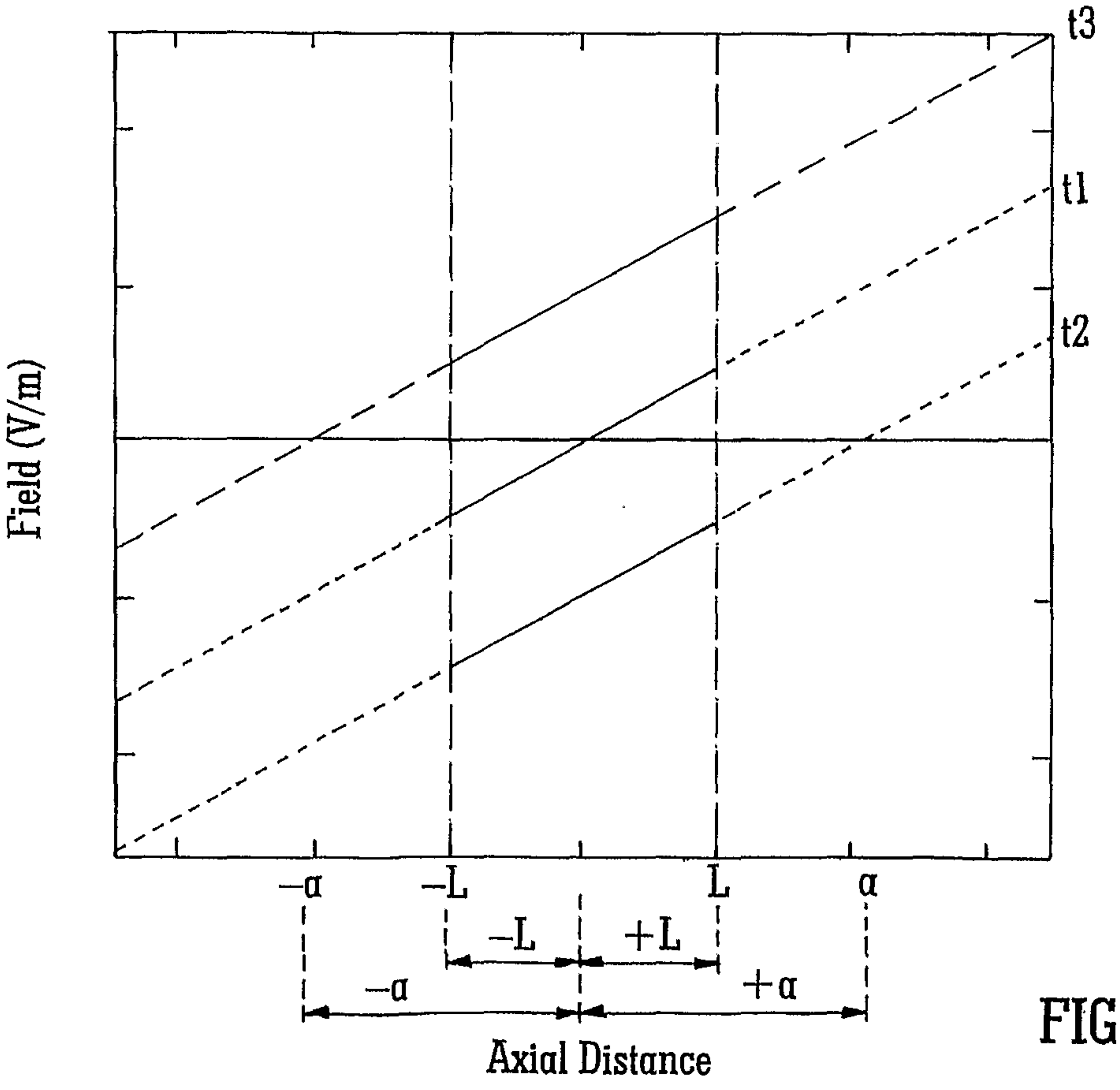

t3
t1
t2
Field (V/m)
−a
−L
L
a
−L
+L
−a
+a
Axial Distance

FIG. 6

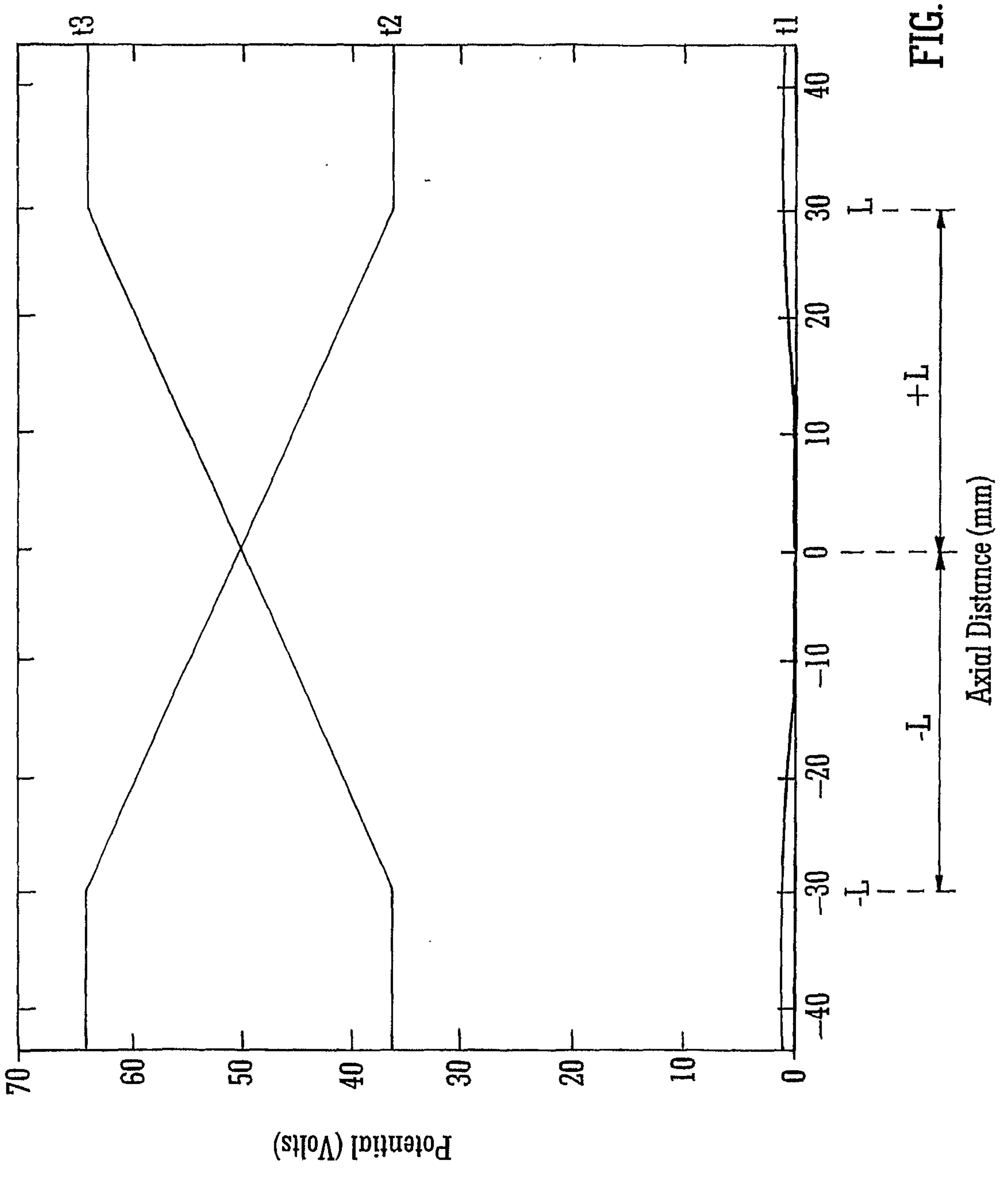

t3
t2
t1
70
60
50
40
30
20
10
0
Potential (Volts)
-40
-30
-20
-10
0
10
20
30
40
-L
L
-L
+L
Axial Distance (mm)

FIG. 7

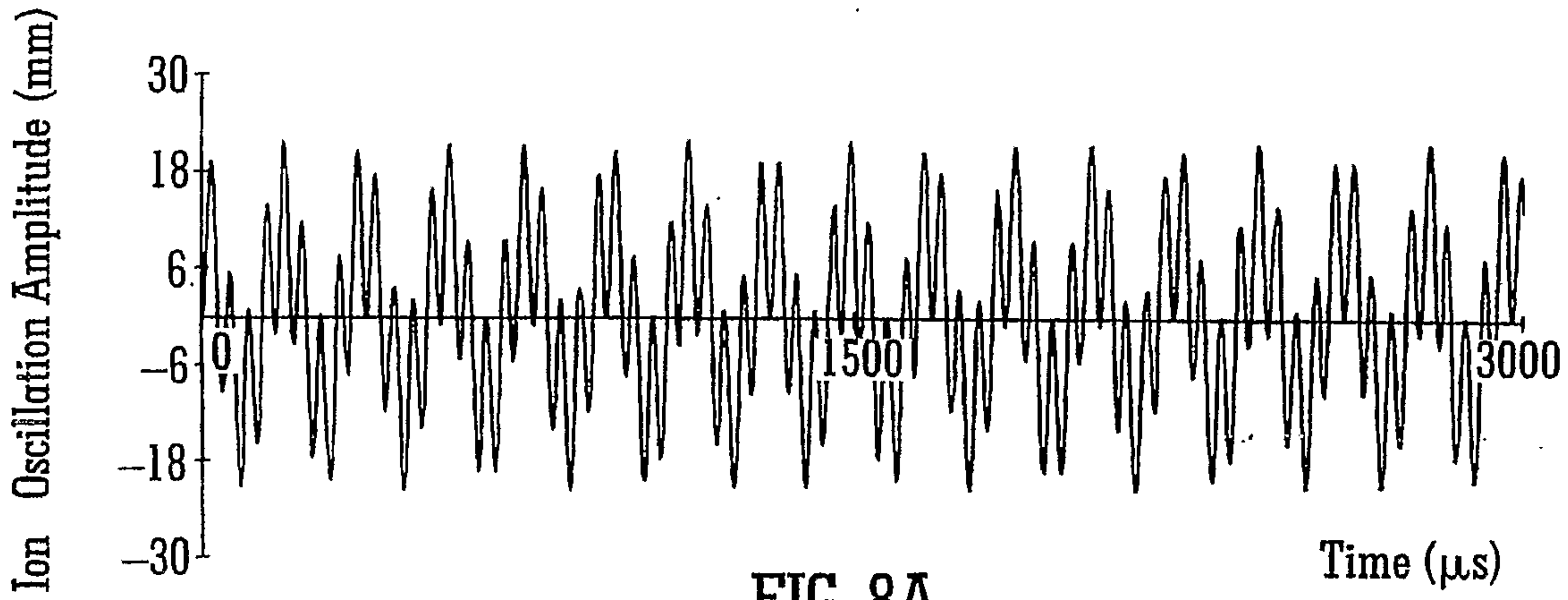


FIG. 8A

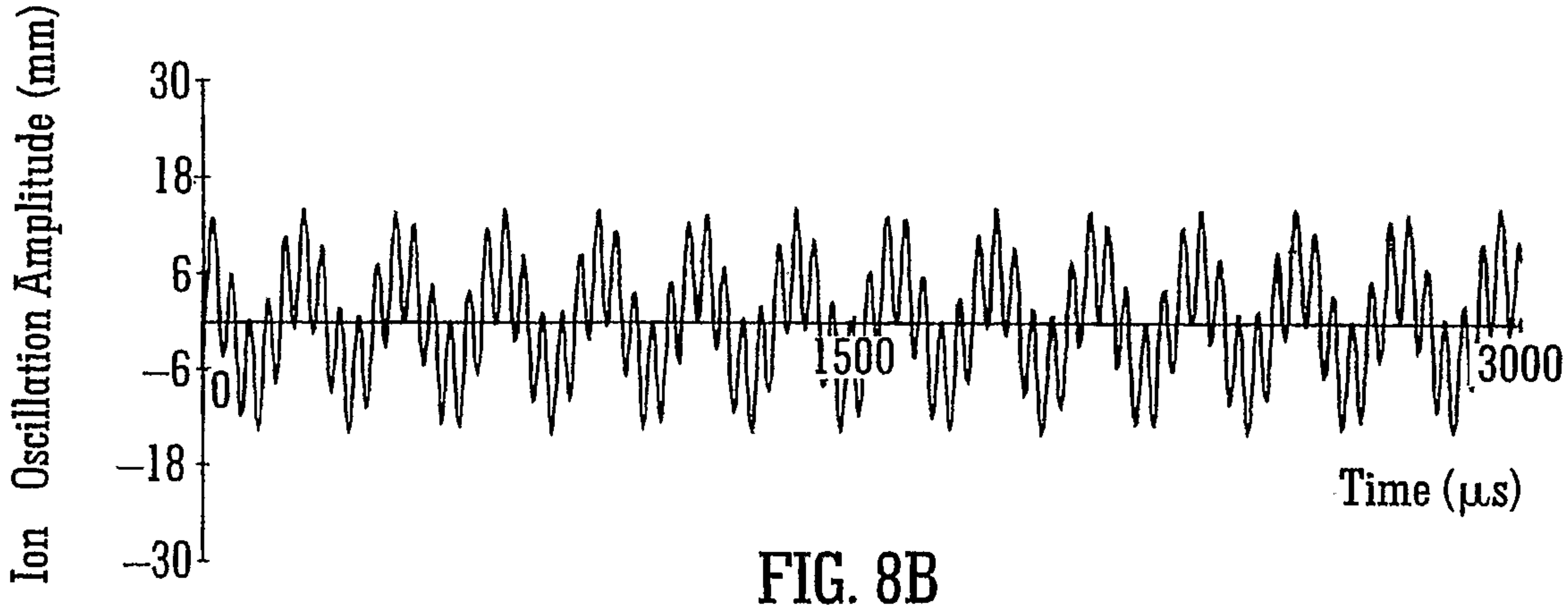


FIG. 8B

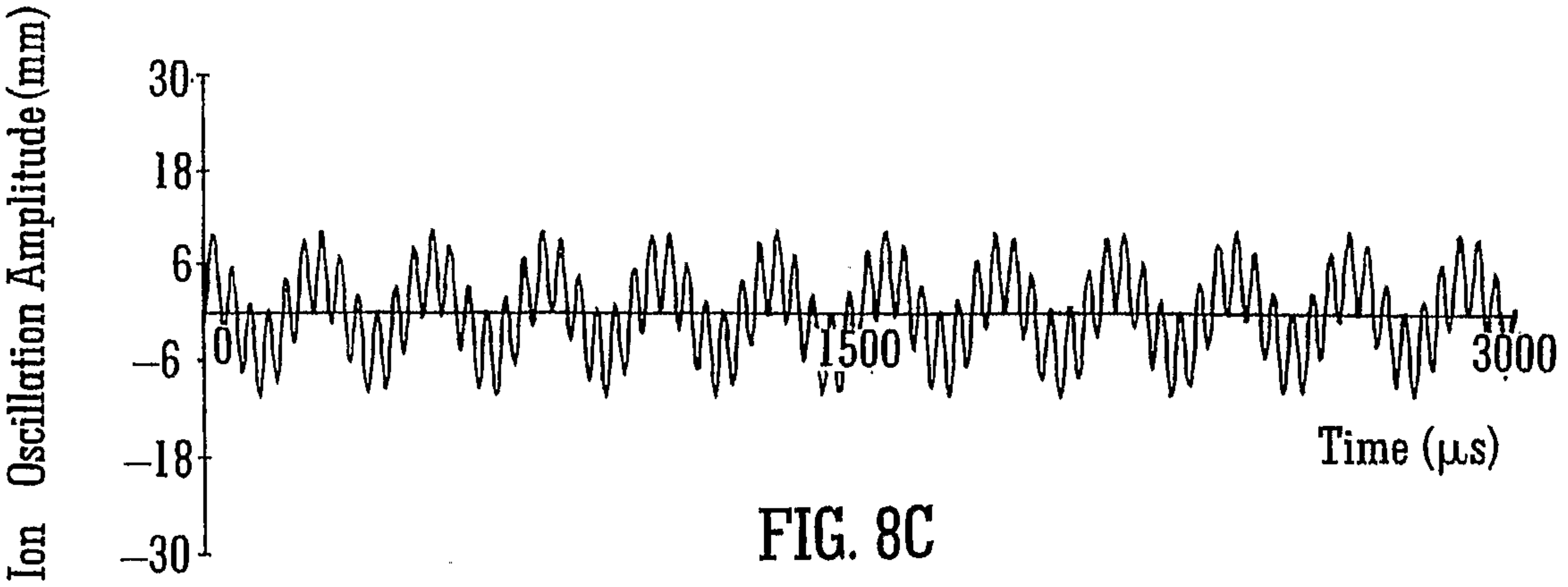


FIG. 8C

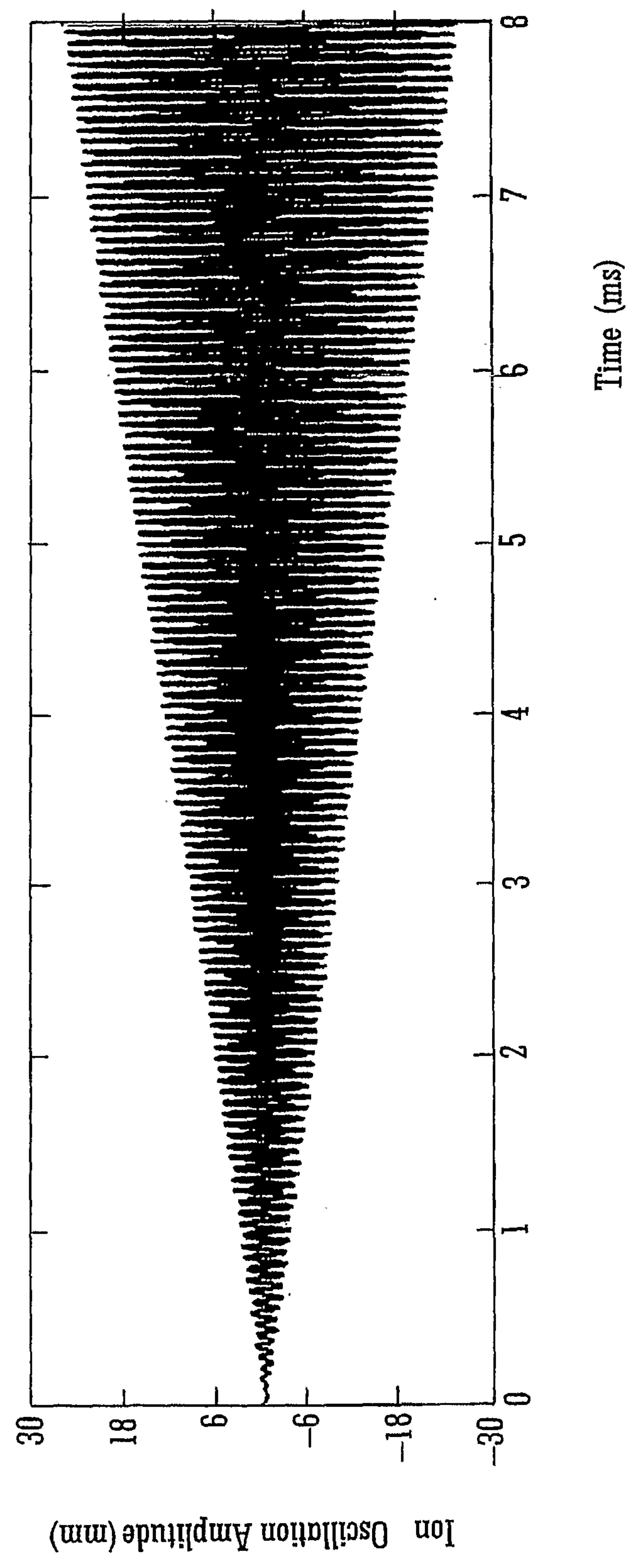

Ion Oscillation Amplitude (mm)
30
18
6
−6
−18
−30
Time (ms)
0
1
2
3
4
5
6
7
8

FIG. 9A

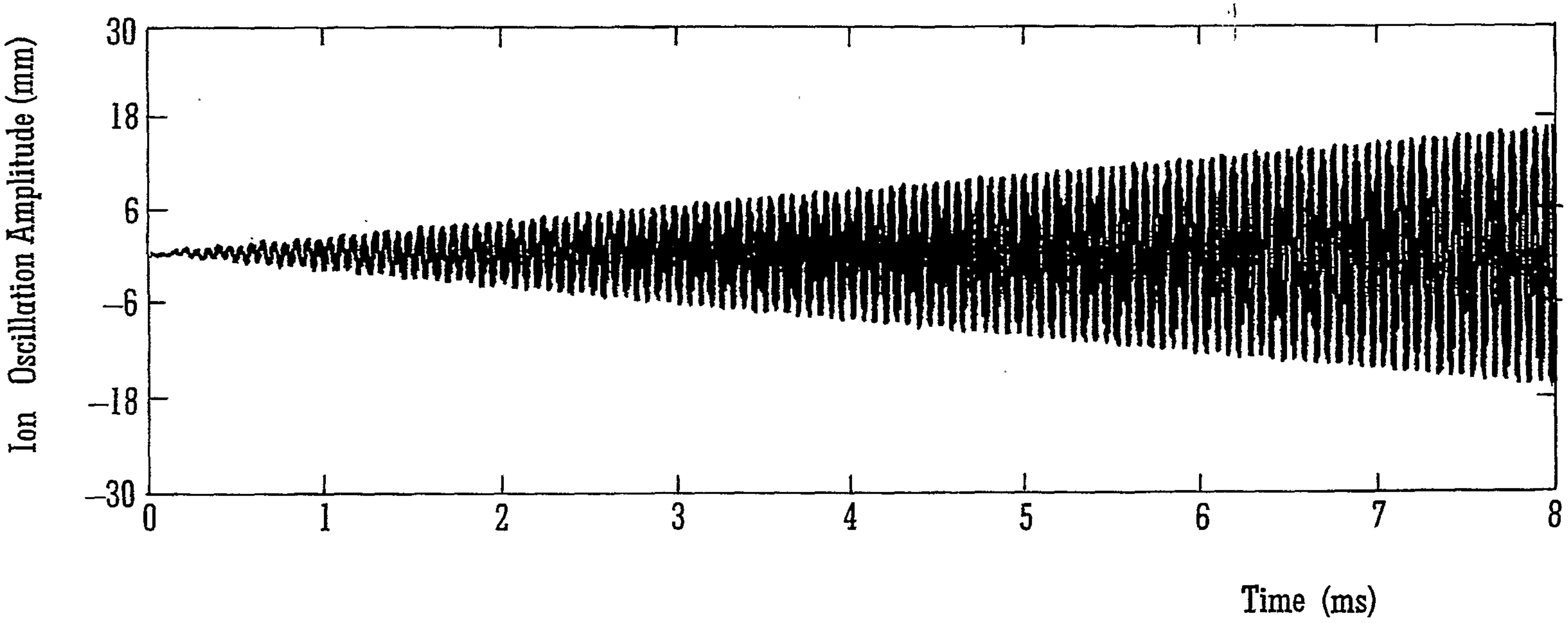

30
18
6
−6
−18
−30
Ion Oscillation Amplitude (mm)
0
1
2
3
4
5
6
7
8
Time (ms)

FIG. 9B

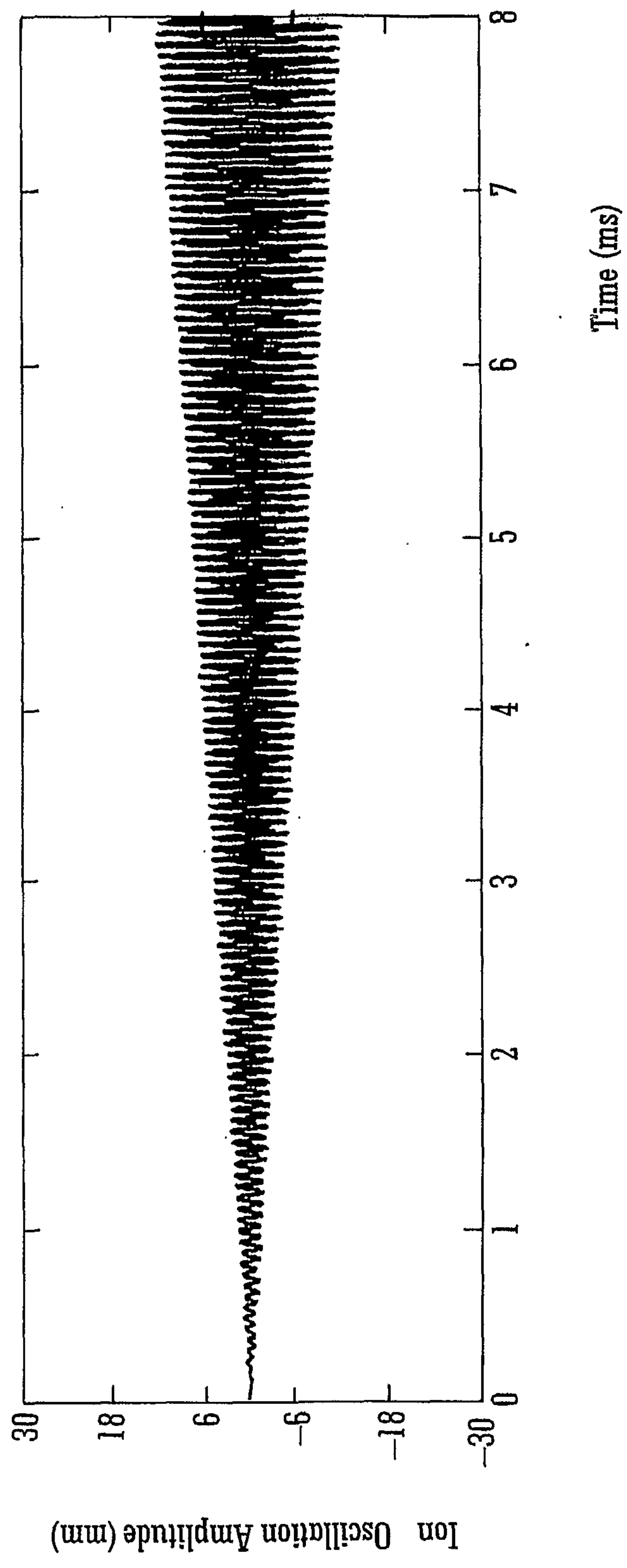

30
18
6
−6
−18
−30
Ion Oscillation Amplitude (mm)
0
1
2
3
4
5
6
7
8
Time (ms)

FIG. 9C

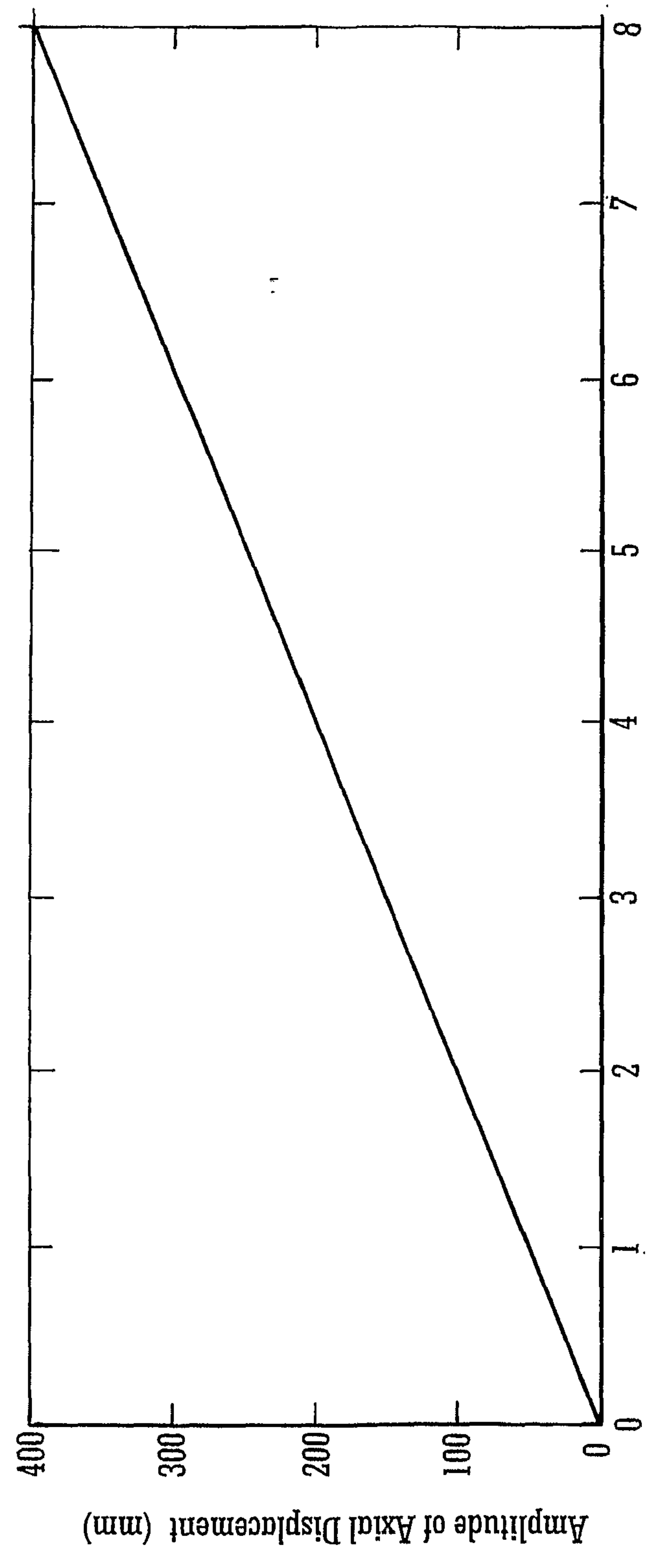

Amplitude of Axial Displacement (mm)
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Time (ms)

FIG. 10

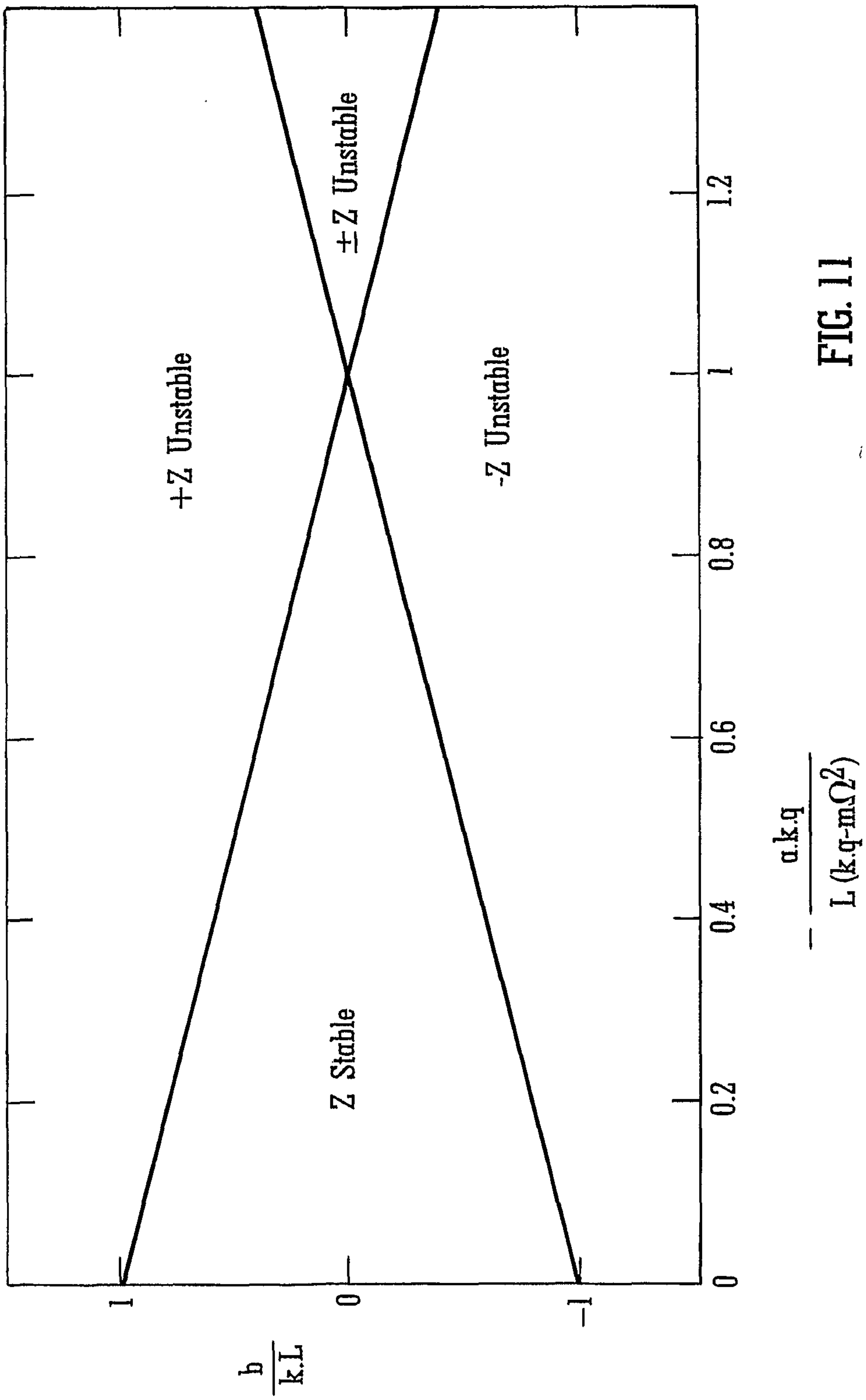
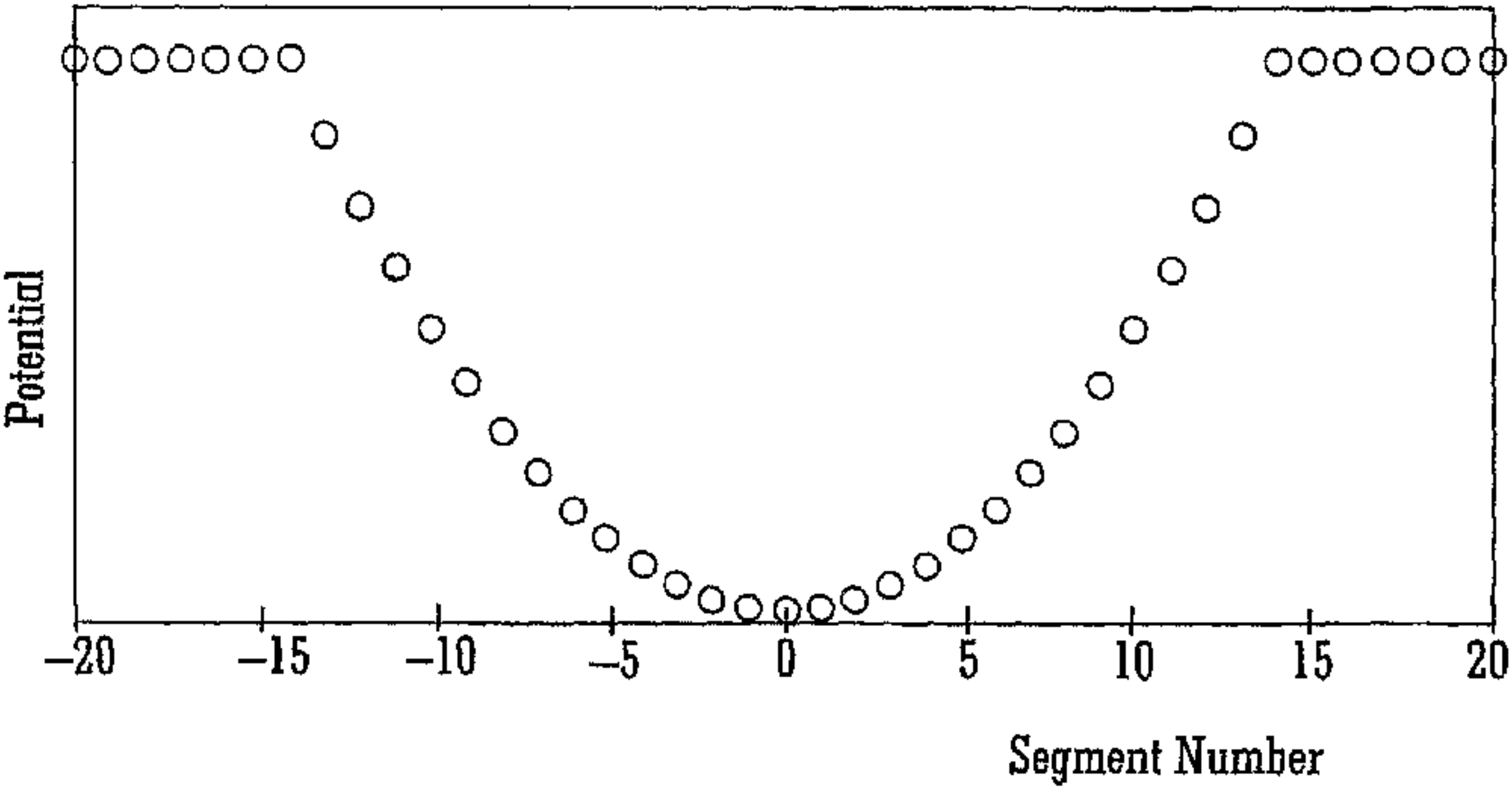

+Z Unstable
±Z Unstable
-Z Unstable
Z Stable
1
0
−1
$\frac{b}{k.L}$
0
0.2
0.4
0.6
0.8
1
1.2
$-\frac{a.k.q}{L\,(k.q-m\Omega^2)}$

FIG. 11


Potential
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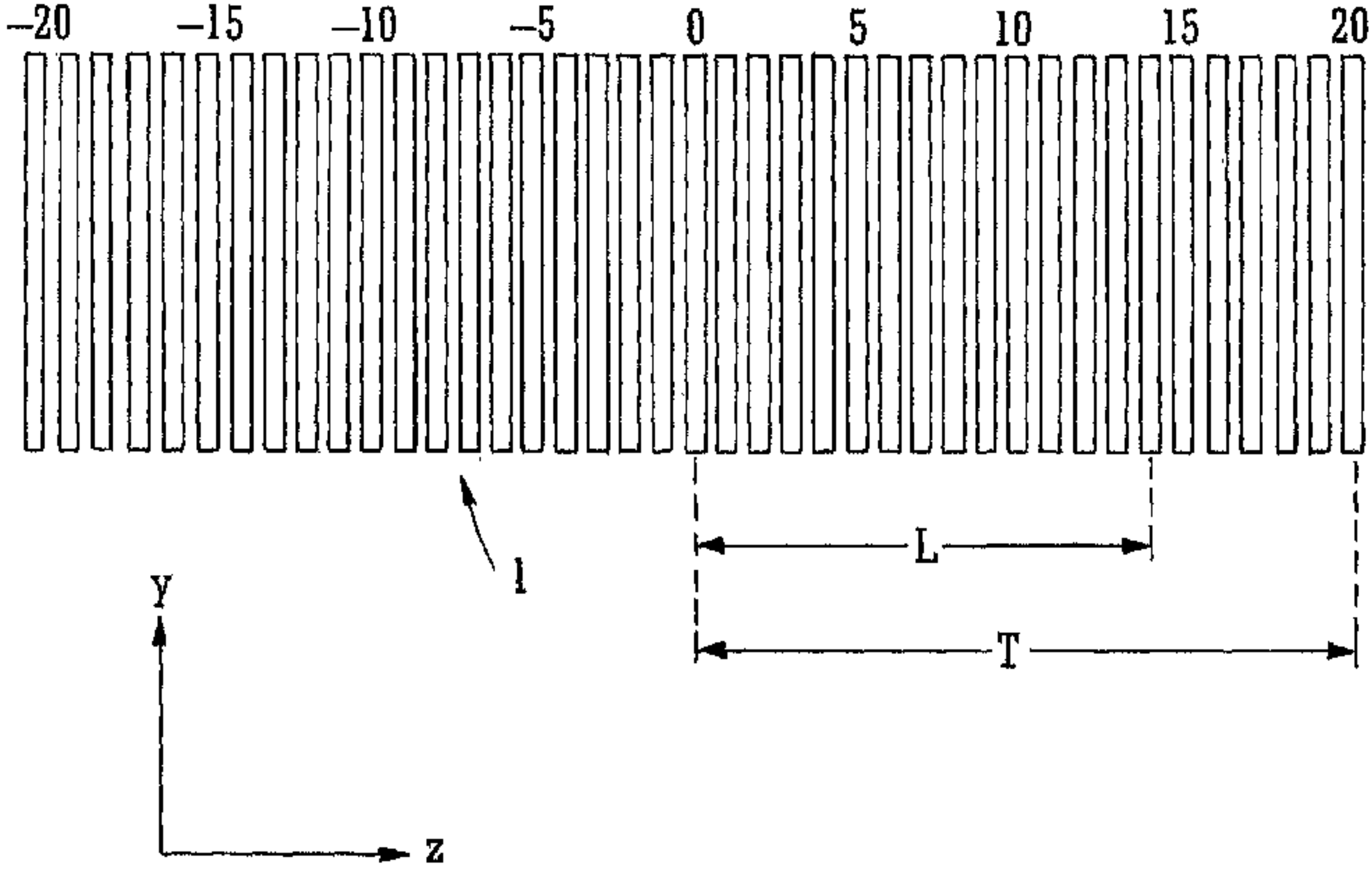
15
20
Segment Number


−20
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−5
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5
10
15
20
l
L
T
y
z