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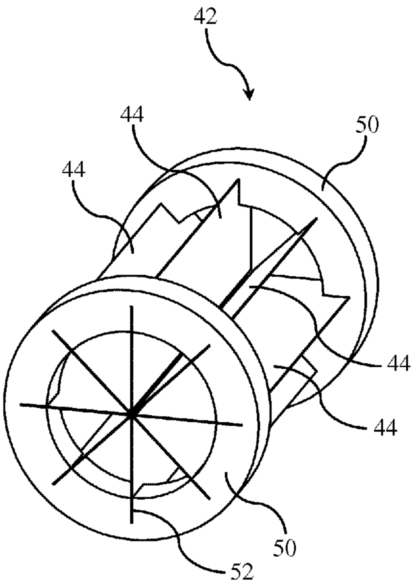

Fig. 2a

(57) Abstract: Disclosed herein is an ion guide (42) for guiding an ion beam along an ion path, said ion guide having a centerline (46) corresponding to said ion path, and a plurality of electrodes extending along said centerline. The electrodes are formed by conductive electrode plates (44) which are radially arranged around said centerline (46), wherein each of said electrode plates (44) has a radially inner edge (48) that is closest to the centerline (46) and a wedge-like profile with a thickness increasing in radially outward direction, and wherein an inner envelope of the radially inner edges (48) defines an ion guide volume. The radially inner edges (48) are, at least in a section along the length of the ion guide (42), conically converging or diverging, forming an angle with the centerline between 0.1° and 45°. Said electrode plates (44) are connected or connectable with an RF voltage source for applying voltages collectively confining ions within said ion guide volume.

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Ion guide comprising electrode plates and ion beam deposition system

FIELD OF THE INVENTION

The present invention relates to an ion guide and an ion guide assembly for guiding an ion beam along a path. In particular, the present invention relates to an ion guide for use in an ion beam deposition system, as well as to an ion beam deposition system comprising such ion guide or ion guide assembly, and to a method for guiding ions employing such ion guide.

BACKGROUND OF THE INVENTION

Ion beams have many uses in various fields of natural sciences and technology, including experimental physics, medical devices, electronic components manufacturing or life science, in particular mass spectroscopy, where electrically charged molecules (ions) are guided to, from or within a mass spectrometer or a collision cell. The general purpose of an ion guide is to confine an ion beam along its predetermined path, typically using a plurality of electrodes arranged around the ion path, which in combination generate an electrical potential guiding the ions. In the simplest case, the potential could be a static DC potential, which would typically be realized as an ion Einzel lens arrangement. This, however, demands a fixed correlation of the ions' radial and axial momentum to keep them on track. Any breaking of this correlation e.g. due to collisions with residual gas atoms makes the ions swerve and lose track. These conditions are very common at relatively high pressure in the first stages of a multistage ion guide system, or in collision cells or drift cells, but can also occur due to space charge effects in later stages.

To make an ion guide more resistant to such perturbations, systems of electrodes can be employed which are driven with radio frequency (RF) voltages having frequencies of about 0.5 to 5 MHz and amplitudes of some volts up to some 100 volts. When the amplitude and the frequency of the RF potential are properly chosen, ions will be effectively repelled from the RF electrodes by means of an effective potential or "pseudo-potential" which reflects the effect of the RF electric field on the ion averaged over a plurality of AC cycles. A repulsive force derivable from this pseudo-potential, the so-called "field gradient force", is proportional to the gradient of the square of the RF field strength, proportional to the square of the charge of the ion - and hence independent of its polarity - and inversely proportional to the ion mass and to the square of the RF frequency.

In most RF operated ion guide systems, adjacent electrodes are driven with sinusoidal voltages of opposite phase, i.e. with a phase shift of 180° in between. For example, in known multipole ion guides, four, six or eight rod electrodes may be arranged on a circle around and extending parallel to the ion path, thereby forming a quadrupole, hexapole or octopole structure, respectively.

While there are many purposes for ion guides in various fields of science and technology, and the present invention is not restricted to use in a specific one of them, the ion guide of the present invention is particularly suitable for use in ion beam deposition (IBD), mass spectroscopy (MS), such as triple quad, Orbitrap or quadrupole time-of-flight (Q-TOF) mass spectroscopy, in ion mobility spectroscopy (IMS) systems and for use as an injection module to a quadrupole mass spectrometer, collision cell or ion trap.

In IBD, ions are guided along an ion path through a series of pumping chambers with decreasing pressure prior to being deposited by means of so-called “soft landing” on a substrate or target. The purpose of the pumping chambers is to remove unwanted, neutral particles from the ion beam. Ion beam deposition has important advantages over conventional deposition techniques. For example, unlike sputtering, plasma spraying, physical vapor deposition (PVD) and atomic layer deposition (ALD), IBD is not restricted to the deposition of thermally stable molecules. Chemical vapor deposition (CVD) requires a chemical reaction between sometimes poisonous educts on the substrate, which can likewise be avoided using IBD. Finally, while spincoating is restricted to (on an atomic scale) large thicknesses, IBD allows for depositing layers of a defined atomic thickness.

Moreover, since an ion beam can be deflected using suitable electric fields, in IBD, it is possible to “write” structures on a substrate, in a way similar to mask free ion beam lithography. Accordingly, it is possible to position highly sensitive, thermolabile molecules with low masses, like amino acids up to molecules with high masses, like peptides, proteins or even DNA molecules with a layer thickness defined on an atomic scale in micro arrays for manufacturing assays, sensors or highly specific catalysts.

All of these advantages of IBD currently come at the price of a rather slow deposition speed, which is due to the limited yield of the IBD system in view of the comparatively low intensity of the ion beam in current IBD systems.

SUMMARY OF THE INVENTION

The problem underlying the invention is to provide an ion guide with improved properties, which in particular allows for increasing the yield of an IBD system, as well as an improved IBD system.

This problem is solved by an ion guide according to claim 1, ion guide assemblies according to claims 21 and 24, as well as by an IBD system according to claim 25 and by a method of guiding an ion beam according to claim 26. Favorable embodiments are defined in the dependent claims.

The ion guide of the invention is suitable for guiding an ion beam along an ion path, said ion guide having a centerline corresponding to said ion path, and a plurality of electrodes extending along said centerline. The electrodes are formed by conductive electrode plates which are radially arranged around said centerline. Each of said electrode plates has a radially inner edge that is closest to the centerline and an inner envelope of the radially inner edges defines an ion guide volume. The electrode plates are connected or connectable with an RF voltage source for applying voltages collectively confining ions within said ion guide volume.

The ion guiding potentials that can be generated with this type of ion guide is similar to potentials that could be generated using longitudinal rod electrodes located at positions corresponding to the radially inner edges of the electrode plates. However, the inventors found out that for the purpose of increasing the yield of an IBD system or related applications, an ion guide based on elongate rod electrodes arranged on a cylindrical surface around the ion beam path should preferably have a comparatively large number of electrodes that are arranged closely together and confine an ion guide volume that has a fairly small cross-section. In fact, the inventors have found that a preferable ion guide would require “electrode rods” that are so thin that they are formed as wires that need mechanical tensioning and straightening rather than ordinary rod electrodes. Corresponding ion guides and applications are the subject of the co-pending application *Ion guide comprising electrode wires and ion beam deposition system.*

The importance of closely spaced elongate electrodes, and hence the motivation of using “electrode wires” instead of “electrode rods” can be understood as follows. The yield of an IBD system is governed by the ion current that can be guided through the ion guide or ion guide arrangement, which is referred as the “current capacity” of the ion guide (arrangement) herein. The obvious way to increase the current capacity would be to increase the diameter of the ion guide as a whole. However, when the diameter of the ion guide increases, the diameters of apertures in separation walls separating adjacent pumping chambers likewise need to be made correspondingly larger. This in turn makes it more difficult to decrease the number of neutral particles in the ion beam by means of pumping. The flow of neutral particles in common with the ion beam is referred to as “gas load” in the following. In other words, the inventors noticed that when increasing the diameter of the apertures in the separation walls, eventually more pumping stages were necessary to reduce the gas load to a desired degree. A larger number of pumping chambers however increases the manufacturing and operating costs and extends the ion path, leading to an inherent increase of ion losses.

Accordingly, the inventors realised that it is not possible to optimise the current capacity in a straightforward way by simply increasing the diameter of the ion guide. The inventors have further found that, at a given ion guide diameter, the current capacity is increasing with increasing number of elongate electrodes. In addition, the inventors have found that optimum results can be achieved with a moderate diameter of the ion guide, but comparatively large numbers of elongate electrodes. Then, when also choosing optimum inter-electrode distances, the inventors found that in favourable ion guides, the elongate electrodes should be made thinner than conventional rod electrodes, and in fact be formed by electrode wires which are so thin (and hence flexible) that they need tensioning to be kept straight, as is described in the co-pending application *Ion guide comprising electrode wires and ion beam deposition system.*

While the wire-based ion guides disclosed in the co-pending application have proven to be highly advantageous, the mounting of the electrode wires is somewhat involved. It requires certain holding structures that both hold the electrode wires as well as apply mechanical tension to the electrode wires to keep them straight. Moreover, when devising the holding structures, care must be taken that any insulating parts of the holding structures are sufficiently far away from the ion guide volume such as to avoid that the holding structures are charged by stray ions from the ion beam, which would lead to a distortion of the electric field for guiding the ion beam and in consequence to a reduction of the current capacity.

The inventors however noticed that using the design of the present invention employing radial electrode plates allows for obtaining similar guiding potentials, since the radially inner edges of the electrode plates can be arranged similarly closely together than the electrode wires of the wire based ion guides, and this can be obtained with considerably less mechanical effort, because unlike the wire based ion guides, no tensioning mechanism is needed. Moreover, due to the radial arrangement, the electrode plates can be easily mounted at a radially outside portion which is sufficiently far away from the ion guide volume such that there is no risk of charging by stray ions. Accordingly, similar advantages can be obtained as in the case of the wire based ion guide of the co-pending application, but with less constructional and manufacturing effort. Furthermore the electrode plates can be modelled in ways that conical or more complex shapes of the inner envelope along the longitudinal axis can be generated easily.

Since the electrode plates employed in the ion guide of the invention tend to be rather thin, and since it is particularly the location of the radially inner edge of the electrode plates that dominates the generated ion guiding potential, the “electrode plates” are also referred to as “blades” herein, and the corresponding ion guide is referred to as a “Blade Ion Guide (BIG)”.

In preferred embodiments, the aforementioned radial arrangement of the electrode plates or “blades” is radial in a strict sense, meaning that for each electrode plate, there exists a radius vector pointing radially outward from said centerline and lying within said electrode plate. This “precisely radial” arrangement is the preferred arrangement that has been employed in various embodiments of the present invention disclosed herein. Nevertheless, it may be possible to obtain similarly good or only moderately inferior results when slightly deviating from this “precisely radial” arrangement. Accordingly, when referring to electrode plates that are “radially arranged around the centerline”, this is to be understood in the sense of “substantially radial”, permitting some deviations from the “precisely radial” arrangement, as long as the ion guiding potential generated thereby is not significantly affected by the deviation from the “precisely radial” arrangement.

In preferred embodiments, said centerline is a straight line defining a longitudinal axis of said ion guide. However, in alternative embodiments, said centerline may be a curved line. By suitably forming the shape of the radially inner edges of the electrode plates, such curved centerlines can be easily obtained. This is another particular advantage over the wire based ion guides referred to above, where curved centerlines are much more difficult to achieve.

In each section plane along the length of and perpendicular to the centerline, the distances of the radially inner edges of the electrode plates from the centerline is preferably identical, or varies by less than 15%, preferably by less than 10%. If the distances are all identical, then the “inner envelope” of the radially inner edges of the electrode plates in each section plane could be regarded as the largest circle that touches the radially inner edges of all of the electrode plates. However, in order to also allow for embodiments where the distances vary to some extent, according to the present disclosure the “inner envelope” of the radially inner edges of the electrode plates will be regarded as a polygon having as many vertices as there are electrode plates, and wherein each of the vertices is located on a radially inner edge of a corresponding one of the electrode plates. Moreover, this "inner envelope" defines the "ion guide volume" as used herein.

In preferred embodiments, the ion guide further comprises a holding structure for holding the electrode plates, wherein a portion of said holding structure, *if any*, which is separated from said inner envelope by less than the local inter-plate distance, preferably by less than twice the local inter-plate distance, and most preferably by less than three times the local inter-plate distance is made from a material having an electrical resistivity of less than 10^{12} Ohm·cm, preferably of less than 10^{9} Ohm·cm. A similar effect can be obtained if a portion of said holding structure, *if any*, which is separated from said inner envelope by less than the local inter-plate distance, preferably by less than twice the local inter-plate distance, and most preferably by less than three times the local inter-plate distance has a sheet resistivity of less than 10^{14} Ohm, preferably of less than 10^{10} Ohm on a surface facing said ion guide volume, preferably on any surface facing said ion guide volume. Herein, the local inter-plate distance is defined as the distance between the radially inner edges of adjacent electrode plates at a given axial position. If at some axial position the distances between the radially inner edges of adjacent electrode plates should be nonuniform, the "local inter-plate distance" corresponds to the average thereof.

Note that according to this embodiment, the holding structure may be of a type which in its entirety is located further away from the inner envelope than said multiples of the inter-plate distance, or in other words, of a type where there is no portion thereof which would be separated from the inner envelope by less than said multiples of the inter-plate distance. This variant is accounted for by the "if any" condition. In this variant, the material of the holding structure may be insulating, because it is sufficiently far away from the ion guide volume such that there is no risk that it is hit and consequently charged by stray ions.

In alternative variants of this embodiment, some portions of the holding structure may indeed be separated from the inner envelope by less than the aforementioned multiples of the inter-plate distance, which bears the risk that these portions could be hit by stray ions. However, in this case the resistivity of such portions is chosen to be less than 10^{12} Ohm·cm, preferably less than 10^{9} Ohm·cm, such that no significant charging is caused even if this portion is hit by stray ions. Another way of providing for an effective draining of possible stray ions is by means of a sheet resistivity of less than 10^{14} Ohm, preferably less 10^{10} Ohm on any surface facing said ion guide volume. This can be achieved by a suitable coating. The coating may e.g. be a metal film having a thickness of 30 to 1000 nm, or a paste containing glass and metal oxides, wherein said paste preferably has a thickness of 5 to 1000 μm.

In preferred embodiments, the holding structure comprises ring-like elements having slots in which the electrode plates are received. Using ring-like elements, the electrode plates or “blades” can be mounted at a radially outside portion thereof, which is sufficiently far away from the ion guide volume such that there is no risk of being hit by stray ions.

In preferred embodiments, the electrode plates have one of

- a uniform thickness, and
- a wedge-like profile with a thickness increasing in radially outward direction.

Accordingly, in the framework of the present invention, the term “plate” does not require a uniform thickness, but it also covers structures having nonuniform, wedge-like profiles. A wedge-like profile allows for a thin radially inner edge and concurrently provides more structural support by an increased thickness in radially outward direction. In case the electrode plates or “blades” have a wedge-like profile, in a cross-section perpendicular to the centerline, the wedge-like profiles may form angular sections with gaps in between, wherein at any given circle around the centerline, the ratio between the width of the angular sections in circumferential direction and the width of an adjacent gap is between 0.5 and 6.0, preferably between 0.8 and 4.0. This design leads to a constant ratio between the blade section and the gap section at the inner end of the wedge like blades, even if their inner envelope is not constant, particularly in case of a conical profile of the inner envelope along the longitudinal axis and thus leads to optimum current capacity of the ion guide.

In preferred embodiments, the electrode plates have a pointed tip formed by an acute angle between the radially inner edge of the electrode plates and an adjacent edge portion of said electrode plate on at least one of the longitudinal ends of the ion guide, wherein the acute angle is 70° or less, preferably 50° or less, and most preferably 30° or less. This pointed tip is particularly useful for receiving an ion beam from or transmitting an ion beam to an adjacent ion processing system, such as another ion guide, an ion separation system, an ion analysis system, an ion deposition system or an ion collision system. Herein, the pointed tip can be located closely adjacent to an entrance or exit of said further ion processing system, to thereby keep losses at the transitions between the ion guide and the further ion processing system at a minimum. The pointed tip is also useful for feeding an ion being through an aperture in a separation wall between two adjacent pumping chambers, as will be further illustrated below.

In a preferred embodiment, the radially inner edges of the electrode plates are, at least in a section along the length of the ion guide, conically converging or diverging from the centerline, wherein the average angle between the radially inner edges of the electrode plates and the centerline within said section is less than 45° preferably less than 5°, and most preferably less than 1°, and is 0.1° or more, preferably 0.2° or more, and most preferably 0.5° or more. For example, a wide end of a conical ion guide structure may facilitate feeding an ion beam into said ion guide and is less sensitive to slight misalignments of the ion guide with respect to an upstream component or allows for compressing the ion beam to a lower cross section. At the same time, keeping the angle between the radially inner edges of the electrode plates and the centerline below 5°, or even below 1° allows for keeping a repulsive force along the longitudinal axis due to the converging radially inner edges of the electrode plates in the direction of travel within acceptable bounds.

In a preferred embodiment, the number of electrode plates is 6 or more, preferably 8 or more, more preferably 10 or more, and most preferably 12 or more. With higher numbers of electrode plates, the current capacity of the ion guide for a given diameter of the ion guide volume can be increased. Note that due to the radial structure of the ion guide, the mounting of a comparatively large number of electrode plates with their radially inner edges arranged closely together can still be achieved with comparatively low mounting effort, at a high precision and without the risk that holding or mounting structures are inadvertently charged by stray ions

In preferred embodiments, the electrode plates are made from copper, molybdenum, tungsten, nickel, silver, gold, iron or alloys or compounds thereof or are covered with these materials.

In preferred embodiments, the thickness of each electrode plate close to the radially inner edges is 5.0 mm or less, preferably 1.0 mm or less, and more preferably 0.1 mm or less. Herein, the expression “close to the radially inner edge” accounts for the possibility that the radially inner edge is rounded, in which case the thickness is to be determined sufficiently away from the apex of the radially inner edge to be outside such possible rounded portion, such that a meaningful thickness can be determined. If the radially inner edges are not rounded, and a meaningful thickness can be determined at the radially inner edge, then the expression “close to the radially inner edge” may include the special case of “at the radially inner edge”. It is emphasized that the comparatively small thicknesses of the electrode plates at or at least close to the radially inner edge allows for a comparatively large number of electrode plates at a comparatively small cross-section of the ion guide volume. When moving away from the radially inner edge, as mentioned above, the thickness of the electrode plate may increase, for example in favour of increased rigidity or structural support, to thereby lead to a wedge-like profile.

In a preferred embodiment, the ratio of the thickness of each electrode plate close to its radially inner edge and the inter-plate distance, at any given position along the centerline, is between 0.5 and 6.0, preferably between 0.8 and 4.0, wherein the inter-plate distance is defined as the distance between the radially inner edges of adjacent electrode plates at a given position along said centerline. These ratios of electrode plate thickness and inter-plate distance have been found to be beneficial for a high current capacity of the ion guide. Using electrode plates which have small thicknesses at or close to the radially inner edges of 5.0 mm or less, preferably of 1.0 mm or less and most preferably of 0.1 mm or less, these ratios can be achieved in spite of comparatively large numbers of electrode plates in combination with moderate ion guide diameters.

As explained above, the "inner envelope" may be confined, in each section perpendicular to said centerline, by a polygon having as many vertices as there are electrode plates, and wherein each of the vertices is located on a radially inner edge of a corresponding one of the electrode plates. Herein, the cross-section area of this inner envelope at the narrowest position along the centerline is preferably less than or equal to 200 mm^2, more preferably less than or equal to 20 mm^2, and most preferably less than or equal to 2.0 mm^2; and is preferably larger than or equal to 0.1 mm^2, more preferably larger than or equal to 0.2 mm^2, and most preferably larger than or equal to 0.5 mm^2.

In a preferred embodiment, said electrode plates are connected to an RF driving source configured to drive adjacent two electrode plates with voltages of freely adjustable radiofrequency. In particular, said RF driving source may be configured to drive the electrode plates with an RF square wave signal, or a superposition of RF square wave signals, and preferably with a selectable duty cycle. A nonlimiting example of a "superposition of square wave signals" is a so-called "digital signal" which corresponds to a superposition of square waves with different amplitude and different duty cycle, but at the same base frequency.

Note that RF square wave driving signals or superpositions thereof are uncommon for conventional ion guides, where the electrodes are usually resonantly driven, using an LC circuit established by adding an inductive element and using the inherent capacitance of the electrodes for adjusting the resonance frequency. The inventors have noticed that the specific waveform (i.e. square wave digital waveform versus sinusoidal) has little bearing on the current capacity of the ion guide, but the square wave driving signal can be generated more easily with freely adjustable frequency than a sinusoidal driving signal. In fact, square wave signals can be generated by using switching circuits only, without having to provide for any resonant LC elements. Since the switching frequencies, the duty cycle and the superposition of square waves can be freely adjusted, the digital waveform or any other superposition of square waves can likewise be freely adjusted to thereby provide for optimum ion guiding performance.

In preferred embodiments, the electrode plates are connected to an RF driving source which supplies RF voltages having frequencies freely adjustable between about 0.05 to 20 MHz and/ or waveforms freely superimposed by square waves.

For applying a driving force on the ions in longitudinal direction of the ion guide, a DC electric field may be established along the centerline of the ion guide. For this purpose, in a preferred embodiment, at least some of the electrode plates are segmented, having conductive portions separated by intermediate portions of lower conductivity, in particular insulating portions, and different DC voltages are applied to different conductive portions, to thereby generate an electric field along the length of the electrode plate.

In a preferred embodiment, said ion guide is part of an ion beam deposition system, in which an ion beam is guided through a plurality of pumping chambers of decreasing pressure, wherein adjacent pumping chambers are divided by separation walls having an aperture for the ion beam to pass through.

A further aspect of the present invention relates to an ion guide assembly comprising two or more ion guides according to one of embodiments described above, wherein said two or more ion guides are arranged with their centerlines aligned with each other at the respective adjacent ends of said at least two ion guides, wherein said adjacent ends of the at least two ion guides are separated in a direction along said centerlines preferably by at least 0.01 mm and preferably by less than three times, more preferably by less than two times and most preferably by less than (one times) the square root of the cross-section area of the inner envelope of the corresponding end of one of the adjacent the ion guides. Herein, the “end” of a respective ion guide may be defined by the end of the respective electrode plates. Moreover, the adjacent ion guides may be separated by a gap, by an insulating material or by a material having an electrical resistivity of less than 10^{12} Ohm·cm, preferably of less than 10^9 Ohm·cm.

In a preferred embodiment of said ion guide assembly, adjacent ones of said two or more ion guides are arranged in adjacent pumping chambers which are separated by means of a separation wall, wherein an aperture is provided in the separation wall permitting ions guided by said adjacent ion guides to traverse from one pumping chamber into the other. The diameter of said aperture in the separation wall may be 4.0 mm or less, preferably 3.0 mm or less, and more preferably 2.0 mm or less.

A further aspect of the invention relates to an ion guide assembly comprising

- an ion guide according to one of the above-described embodiments having a pointed tip, and
- a further ion processing system selected from a group consisting of another ion guide, an ion separation system, an ion analysis system, an ion deposition system and an ion collision system,

wherein said pointed tip is located adjacent to an entrance or exit of said further ion processing system.

A further aspect of the invention relates to an ion beam deposition system comprising at least one ion guide or ion guide assembly according to one of embodiments described above.

A further aspect of the invention relates to a method of guiding an ion beam along an ion path, said ion guide having a centerline corresponding to said ion path, and a plurality of electrodes extending along said centerline, wherein said electrodes are formed by conductive electrode plates which are radially arranged around said centerline, wherein each of said electrode plates has a radially inner edge that is closest to the centerline, and wherein an inner envelope of the radially inner edges defines an ion guide volume, wherein each adjacent two electrode plates are driven with RF voltages of opposite polarity, in particular with an RF square wave drive signal, or a superposition of RF square wave drive signals, and wherein the method preferably further comprises a step of adjusting the frequency and the voltage amplitude of the drive signal depending on the type of ions to be guided by said ion guide. Herein, said ion guide is preferably an ion guide according to one of the embodiments recited above.

Beyond reduced losses and improved guiding capacity of the ion guides used in an IBD system, the inventors noted that the intensity of the ion beam depends upon the number of ions supplied to the system. In case of a commonly used electrospray ionization (ESI) source, the ions are supplied in an electrolytic solvent provided by a tiny, cannula-like emitter with an inner diameter between 100 µm and 1 µm (nano spray). A small syringe pushes the liquid towards the tip of the emitter. In front of the emitter, with its opening located in ambient pressure, a conductive capillary with an inner diameter between 0.5 mm and 1 mm is located in a distinct distance. Said capillary transfers small droplets extracted from the emitter from ambient pressure into the first pumping stage of an ion guide. The droplets are generated at the surface of the tip of the emitter due to a high voltage applied between the electrolytic solvent and the facing capillary. The electric force to a suitable charged particle in the electrolyte forms a protrusion at the surface of the liquid, limited by its surface tension. In case of a suitable high voltage of 2-3 kV and a suitably pushing syringe, charged droplets with a typical size of 1 µm are sprayed from the tip of the emitter. The solvent evaporates in the following, the droplets undergo a coulomb explosion as the neutrally evaporating solvent leaves an overcharged droplet. After further evaporation of solvent a single molecule has been ionized in a very gentle way, whilst protected by charged solvent.

This sophisticated process takes place in front of and inside the capillary. The evaporating droplets are embedded in a stream of neutral gas, commonly air, which is dragged into the capillary by the pressure difference between its ends (its first end is typically located in ambient pressure, its second end is located in a reduced pressure of the first pumping stage of an ion guide arrangement). Inside the capillary the stream of neutral gas with the embedded droplets and ions respectively is accelerated while moving to its outlet obeying the continuity equation. Thereby the laminar movement of the gas passes over to a turbulent movement and reaches the speed of sound before the gas pours into the first pumping stage with the first ion guide.

The axial movement is superimposed by a radial expansion of the ion cloud due to the repulsion of equally charged ions. The ions tend to touch the inner wall of the capillary, particularly in case of high ion beam intensities, where they are discharged and get lost. This discharging is the most striking problem in the ESI process, especially in case of long, narrow capillaries, suitable for high pressure differences between the inlet and outlet. In a sophisticated arrangement described in WO 2013/124364, the inlet of the capillary is shaped like a continuously converging funnel. The gas flow stays in touch with the inner wall, no abrupt ion movement is necessary to follow the gas flow, few turbulences are generated.

According to a further aspect of the invention, a tube-like device for transferring ions generated by an ion generation source at the first pressure, in particular atmospheric pressure, into a chamber with the second pressure that is lower than the first pressure is provided, which can be used to replace the aforementioned capillaries currently used in ESI processes and related applications. The tube-like device has an inlet for receiving ions generated by said ion generation source at said first pressure, an outlet through which said ions can be emitted towards said chamber with said second pressure, and a wall enclosing a lumen in a tube-like fashion, said lumen extending from said inlet to said outlet, wherein a set of electrodes is integrated with said wall, wherein said electrodes are connected or connectable with an RF voltage source for applying voltages collectively defining an effective potential repelling said ions from said wall.

Preferable embodiments and applications of tube-like devices according to this aspect of the invention are described below. Note that any combinations of these individual embodiments that are technically feasible are likewise part of the present disclosure, without further mention.

In a preferred embodiment, said ion generation source is configured for generating charged droplets and/or ions and/or polarizable particles, in particular by means of generating an aerosol comprising an analyte and a carrier material within a background gas, wherein said carrier material is preferably a volatile fluid, and in particular water and/or other solvents, and wherein said ion generation source is preferably further configured for removing at least part of the carrier material by applying heat and/or a vacuum.

In a preferred embodiment, said ion generation source is one of an electrospray ionization source, a physical ionization source, a chemical ionization source, and a cluster source.

Herein, said electrospray ionization source comprises an emitter having an inner diameter between 0.2 µm and 300 µm, preferably between 1 µm and 100 µm, for emitting a liquid of ions in an electrolytic carrier solvent, and a syringe for pushing said liquid towards a tip of said emitter.

In a preferred embodiment, said electrodes are separated by, and preferably embedded inside a wall-forming material forming at least part of said wall, wherein said wall-forming material is preferably heat resistant up to at least 200°C and/or resistant against solvents. Herein, said electrodes may have a radially inner electrode surface facing said lumen, wherein said radially inner electrode surface is flush with the adjacent wall-forming material, or extends over the wall-forming material towards the lumen.

In preferred embodiments, said wall-forming material has an electrical resistivity of less than 10^{12} Ohm·cm, preferably of less than 10^{9} Ohm·cm, or has a sheet resistivity of less than 10^{14} Ohm, preferably of less than 10^{10} Ohm on a surface facing said lumen, wherein said sheet resistivity may be an implicit sheet resistivity or a sheet resistivity caused by coating.

In preferred embodiments, said wall-forming material is a molding material.

In preferred embodiments, at least one, preferably both of said wall-forming material and the material forming said electrodes is suitable for 3D printing or any other additive manufacturing method, and in particular a material comprising one of a ceramic materials like Al2O3, ZrO2, Y2O3, SiC, Si3N4, BN, B4C, CaB6, TiB2, ZiB2, Ni, composites or combinations thereof, a plastic material like ABS, PLA, PEEK, CFR-PEEK, nylon, PVDF, PP, POM, PI, SRP, TPI, PSU, PESU, PPSU, PEI, butenidiol-vinylalcoholcopolymer, PET, polyester, PVA, TPC, HTP, TPE, PHA, HIPS, PC, TPU, PETG, PMMA, ASA, polystyrol, PBI, SAN, PVC, PPO, PPM, PAI, PBS, PBT, PA, PEX and copolymers and composites thereof or composites with other materials such as ceramics, possibly mixed with graphene, carbon nanotubes, carbon fibers, soot, graphite or metal or a ceramic material mixed with metal or metal oxides.

In preferred embodiments, an inner diameter of the lumen is, at least in some portions thereof, between 0.1 and 2.0 mm, preferably between 0.15 and 1.5 mm and most preferably between 0.2 and 1.0 mm.

In preferred embodiments, the distance between adjacent electrodes is, at least in some portions of the tube-like device, less than 0.5 times the inner diameter of the lumen, preferably less than 0.3 times the inner diameter of the lumen.

In preferred embodiments, said electrodes are connected to an RF driving source configured to drive adjacent two electrode plates with voltages of opposite polarity,
wherein the amplitude of the driving voltage is preferably between 0.1 and 500 V, more preferably between 5 and 300 V and most preferably between 10 and 100 V,
wherein the frequency is preferably between 0.1 and 50 MHz, more preferably between 5 and 25 MHz, and most preferably between 10 and 20 MHz, wherein the frequency is preferably freely adjustable, wherein said RF driving source is preferably configured to drive the electrodes with an RF square wave signal or a superposition of RF square wave signals, preferably with a selectable duty cycle.

In preferred embodiments, the electrodes are made from copper, molybdenum, tungsten, nickel, silver, gold, iron or alloys or compounds thereof or have a coating of any of these materials.

In preferred embodiments, the diameter of said lumen is varied along the length thereof, wherein particular a funnel structure is formed adjacent to one or both of the inlet and outlet.

In some embodiments of the tube-like device said set of electrodes comprises electrodes extending in lengthwise direction of the tube-like device. Herein, the electrodes may be straight or helically wound around said lumen.

In preferred embodiments, said electrodes are formed by conductive electrode plates which are radially arranged around a centerline of said lumen. Herein, for each electrode plate, there preferably exists a radius vector pointing radially outward from said centerline and lying within said electrode plate.

Some embodiments, said centerline is a straight line defining a longitudinal axis of said lumen. In other embodiments, said centerline is a curved line.

In preferred embodiments, in each section plane along the length of and perpendicular to the centerline, the distances of the radially inner edges of the electrode plates from the centerline is identical, or varies by less than 15%, preferably by less than 10%.

In a preferred embodiment, the electrode plates have one of

- a uniform thickness, and
- a wedge-like profile with a thickness increasing in radially outward direction.

Herein, in a cross-section perpendicular to centerline of the lumen, the wedge-like profiles preferably form angular sections with gaps in between, wherein said gaps are at least partially filled with said wall-forming material, wherein at any given circle around and along the centerline, the ratio between the width of the angular sections in circumferential direction and the width of an adjacent gap is between 0.5 and 6.0, preferably between 0.8 and 4.0.

In a preferred embodiment, at any given circle around and along the centerline, the ratio between the width of the wedge-like electrode plate in circumferential direction and the width of the adjacent gap is identical, or deviates from the average ratio by less than 50%, preferably by less than 20%.

In a preferred embodiment, a portion adjacent to the inlet, the radially inner edges of the electrode plates are diverging from each other in a direction towards the inlet, to thereby form a funnel like structure opening towards the inlet, and/or
in a portion adjacent to the outlet, the radially inner edges of the electrode plates are diverging from each other in a direction towards the outlet, to thereby form a funnel like structure opening towards the outlet,
wherein the opening angle of the respective funnel structure towards the inlet is preferably between 5° and 180°, more preferably between 15° and 120°, and most preferably between 45° and 90°,
wherein the opening angle of the respective funnel structure towards the outlet is preferably between 5° and 90°, more preferably between 20° and 60°, and most preferably between 30° and 55°.

In a preferred embodiment, the number of electrodes extending in lengthwise direction is 4, 6, 8, 10, 12, 14 or 16.

In a preferred embodiment, the ratio of the thickness of each electrode plate close to its radially inner edge and the inter-plate distance, at any given position along the centerline, is between 0.5 and 6.0, preferably between 0.8 and 4.0, wherein the inter-plate distance is defined as the distance between the radially inner edges of adjacent electrode plates at a given position along said centerline.

In another variant of the tube-like device, said lumen extends along a longitudinal axis of said device, wherein said set of electrodes comprises a plurality of electrode plates which are arranged perpendicularly to the longitudinal axis, each electrode plate having an opening and being arranged such that said longitudinal axis extends through its respective opening.

Herein, said annular sealing elements are preferably arranged between adjacent electrode plates, said annular sealing elements forming, together with radially inner edges of said openings, said wall enclosing said lumen in a tube-like fashion.

In a preferred embodiment, some or all of said sealing elements are coated at least on a surface facing said lumen with a coating suitable for draining the charge of stray ions to thereby avoid static charging of said sealing elements by stray ions.

In a preferred embodiment, said coating is a metal film having a thickness of 30 to 1000 nm, or a paste containing glass and metal oxides, wherein said paste preferably has a thickness of 5 to 1000 µm.

In a preferred embodiment, said sealing elements are formed by annular discs, wherein said annular discs preferably serve as spacers to adjust the distance between adjacent electrode plates.

A further related aspect relates to an assembly for generating ions at a first pressure and transferring the generated ions into a chamber with a second pressure that is lower than said first pressure, wherein said assembly comprises an ion generation source, in particular an ion source as defined in one of the above embodiments, and a tube-like device according to one of the preceding embodiments .

A further related aspect relates to a method of manufacturing a tube-like device according to one of above embodiments, wherein said set of electrodes and the remainder of the wall are manufactured by additive manufacturing methods, also known as 3D printing such as powder, filament or fluid methods, for example selective laser sintering (SLS) or selective laser melting (SLM) or electron beam melting (EBM) or stereolithography (STL, STA) or digital light processing (DLP) or fused filament fabrication (FFF) or fused depositoin modelling (FDM) or multi jet modeling (MJM, Polyjet) or film transfer imaging (FTI).

The method preferably further comprises a step of drilling or machining the lumen through the 3D printed or additively manufactured device, wherein preferably, a precursor lumen is provided by the 3D printing or by the additive manufacturing method, and the machining or drilling is carried out to provide for a smoothened wall confining the lumen.

A further related aspect relates to a method of transferring ions generated by an ion generation source at a first pressure, in particular atmospheric pressure, into a chamber with a second pressure that is lower than said first pressure, said method comprising

- receiving ions generated by said ion generation source at said first pressure at an inlet of a tube-like device according to one of the embodiments described above,
- guiding said ions through said tube-like device and
- emitting said ions to said chamber with the second pressure through said outlet of said tube-like device,
- wherein RF voltages are applied to the electrodes of said tube-like device such as to generate an effective potential repelling said ions from the wall of said tube-like device.

Herein, said method preferably further comprises a step of generating ions using said ion generation source, in particular by means of electrospray ionization, physical ionization, chemical ionization or from a cluster source.

SHORT DESCRIPTION OF THE FIGURES

Fig. 1	is a schematic view of an ion beam deposition system employing two blade based ion guides (BIG) according to embodiments of the present invention.
Fig. 2a	is a perspective view of a BIG according to a first embodiment.
Fig. 2b	is a sectional view of the BIG according to the first embodiment.
Fig. 2c	shows an exemplary one of the electrode plates of the BIG of the first embodiment.
Fig. 3a	is a perspective view of a BIG according to a second embodiment.
Fig. 3b	is a view of an exemplary one of the electrode plates of the BIG according to the second embodiment.
Fig. 4a	is a perspective view of a BIG according to a third embodiment.
Fig. 4b	is an enlarged view of the encircled portion of Fig. 4a.

Fig. 4c	shows an exemplary one of the electrode plates of the BIG according to the third embodiment.
Fig. 5a	is a perspective view of a BIG according to a fourth embodiment.
Fig. 5b	is a perspective view similar to that of Fig. 5a, where however only a single electrode plate and a single extension element are shown.
Fig. 5c	is an enlarged view of the encircled portion of Fig. 5a.
Fig. 5d	is a perspective view of an exemplary one of the extension elements employed in the BIG according to the fourth embodiment.
Fig. 5e	shows an exemplary one of the electrode plates as used in the BIG according to the fourth embodiment.
Fig. 6a	is a perspective view of a BIG according to a fifth embodiment.
Fig. 6b	is an enlarged view of the encircled portion of Fig. 6a.
Fig 6c	shows an exemplary one of the electrode plates of the BIG according to the fifth embodiment.
Fig. 7a	is a perspective view of a BIG according to a sixth embodiment.
Fig. 7b	is a perspective view of a ring-like structure for holding electrode plates employed in the sixth embodiment.
Fig. 7c	is a sectional view of an end portion of the BIG according to the sixth embodiment.
Fig. 7d	shows an exemplary one of the electrode plates employed in the seventh embodiment.
Fig. 8	is a perspective view of a BIG according to a seventh embodiment.
Fig. 9	is a circuit diagram showing a driving circuit for driving the electrode plates of a BIG according to various embodiments.
Fig. 10	is a perspective view of a BIG having a conical structure and plates with a wedge-like cross section.
Fig. 11	is a further perspective view of the BIG of Fig. 10.
Fig. 12	is a perspective view of a capillary 30 for transferring ions generated at a high pressure to a chamber with a lower pressure including 16 electrode plates extending in lengthwise direction of the capillary.
Fig. 13	shows a perspective view of a capillary with four electrodes extending in lengthwise direction and having a funnel structure at its inlet.
Fig. 14	is a partly transparent view of the capillary of Fig. 13.
Fig. 15	is a perspective view of a capillary having ring-like electrodes arranged perpendicularly to the longitudinal axis of the capillary.
Fig. 16	is a perspective view of a capillary with ring-like electrodes arranged perpendicularly to the longitudinal axis, and with an inlet funnel structure.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

For the purposes of promoting an understanding of the principles of the invention, reference will now be made to preferred embodiments illustrated in the drawings, and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended, such alterations and further modifications in the illustrated apparatus and such further applications of the principles of the invention as illustrated therein being contemplated as would normally occur now or in the future to one skilled in the art to which the invention relates.

In the figures described below, like elements will be designated with like reference signs, and the description thereof will not be repeated.

Figure 1 shows a schematic illustration of an ion beam deposition (IBD) system 10. The IBD system 10 comprises first to fourth pumping chambers 12 to 18 separated by separation walls 20. Each of the pumping chambers 12 to 18 is connected with a corresponding vacuum pump 22. While all of the vacuum pumps are designated with the same reference sign 22, they may be of different types. On the left end of the IBD system 10, an electrospray ionization (ESI) device 24 is provided, in which molecules are ionized such as to generate the molecular ions to be used for eventual deposition on a substrate 26 located in the fourth chamber 18 at the very right of the figure. The ESI method has first been described in *Malcolm Dole, L.L.Mack, R.L. Hines, R.C.Mobley, D.Furgeson, M.B.Alice, Molecular Beams of Macroions, JChemPhys 49 p. 2240 (1968).* A noble prize had been awarded to John B. Feen for this method, see *John B. Fenn, Electrospray Wings for Molecular Elephants (Nobel Lecture), AngewChemIntEd 42 p.3871 (2003).* In the ESI device 24, charged droplets of an electrolyte are drawn by a very high voltage from a needle 28 which is operated at atmospheric pressure. Herein, the ions are supplied in an electrolytic solvent provided by the needle 28, which is a tiny, cannula-like emitter with an inner diameter between 100 μm and 1 μm (nano spray). As seen in Fig. 1, the ESI device 24 comprises a small syringe which pushes the liquid towards the tip of the emitter or needle 28. In front of the emitter 28, with its opening located in ambient pressure, a conductive and typically heated capillary 30 is located in a distinct distance. Said capillary 30 transfers small droplets extracted from the emitter 28 from ambient pressure into the first pumping chamber 12 of the IBD system 10 shown in Fig. 1. The droplets are generated at the surface of the tip of the emitter 28 due to a high voltage applied between the electrolytic solvent and the facing capillary 30. The electric force to a suitable charged particle in the electrolyte forms a protrusion at the surface of the liquid, limited by its surface tension. In case of a suitable high voltage of e.g. 2-3 kV and a suitably pushing syringe, charged droplets with a typical size of 1 μm are sprayed from the tip of the emitter 28. The solvent evaporates in the following, the droplets undergo a coulomb explosion as the neutrally evaporating solvent leaves an overcharged droplet.

Each droplet includes, in addition to the charged molecules to be deposited, a large amount of unwanted solvent/carrier gas that needs to be removed by means of the vacuum pumps 22 connected to the succession of pumping chambers 12 to 18. The ions and the solvent/carrier gas are guided into the first pumping chamber 12 by means of a heated capillary 30.

The first pumping chamber 12 exhibits a pressure of between 0.1 and 10 mbar. For forming an ion beam, a combined ion funnel and tunnel device 32 is employed, which extends from the first pumping chamber 12 through an aperture in the separation wall 20 into the second pumping chamber 14. The combined ion funnel and tunnel device 32 is referred to as a TWIN guide 32 herein and are described in more detail in the co-pending patent application "*Partly sealed ion guide and ion beam deposition system*".

An electrode wire based ion guide 36 is schematically shown, which extends from the second pumping chamber 14 through an opening in the separation wall 20 into the third pumping chamber 16. Wire based ion guides may be referred to as a “wire ion guide” (WIG) for short and are described in more detail in the co-pending patent application *“Ion guide comprising electrode wires and ion beam deposition system”*. Herein, a portion of the WIG forms an aperture 34 through which neutral gas molecules can inadvertently pass from one chamber to the other.

In the third pumping chamber 16, a quadrupole mass separator 38 is provided, which comprises four rod electrodes 40. Also in the third pumping chamber 16, a first plate or “blade” based ion guide (BIG) 42 according to an embodiment of the invention is shown. As is seen in the schematic representation, the first BIG 42 has a conical ion guide volume with a large diameter at the upstream end facing the quadrupole mass separator 38 and a small diameter at the downstream end facing the separation wall 20 between the third and fourth pumping chambers 16, 18. Moreover, at the downstream end of the first BIG 42, the electrode plates or “blades” have a pointed tip, as will be further explained with reference to more detailed figures below. Finally, a second BIG 42 is provided in the fourth pumping chamber 18, having a conical ion guide volume with a small diameter at the upstream end facing the separation wall 20 between the third and fourth pumping chambers 16, 18, and a large diameter at the downstream end facing and fitting to the substrate 26. Moreover, at the upstream end of the second BIG 42, the electrode plates or “blades” have a pointed tip.

Figure 2a shows a perspective view and Fig. 2b a sectional view of a BIG 42 according to a first embodiment. The BIG 42 comprises 8 electrode plates 44 which are radially arranged around a centerline 46, which is not shown in Fig. 2a and 2b, but schematically shown in Fig. 2c, together with an exemplary one of said electrode plates 44.

Each of the electrode plates 44 has a radially inner edge 48 (see Fig. 2b and 2c) that is closest to the centerline 46. The envelope of the radially inner edges 48 of all electrode plates 44 defines an ion guide volume. The electrode plates 44 are mounted by means of a holding structure comprising two ring-like elements 50 with slots 52 in which the electrode plates 44 are received. As can be seen in Fig. 2a and 2b, the ring-like elements 50 mount the electrode plates 44 at a radially outer portion, which is very far away from the ion guide volume defined by the envelope of the radially inner edges 48 of the electrode plates 44, such that there is no risk that they are hit by stray ions. Accordingly, here the ring-like elements 50 can be made from arbitrary insulating material.

As is seen in Fig. 2a, the electrode plates 44 have a plain or “flat” configuration and are radially arranged with regard to the centerline 46. However, in an alternative embodiment (not shown) it would be possible to twist the electrode plates 44 such as to acquire a slightly helical configuration. This can for example be achieved by rotating one of the ring-like elements 50 around the centerline 46 with respect to the other one. In each sectional plane perpendicular to the centerline 46, the electrode plate 44 would still be arranged radially, such that there is a vector having its origin on the centerline 46 and lying within the twisted plane of the electrode plate 44. The rationale of this twisted arrangement is that the ions tend to acquire less energy when interacting with the AC-field provided by the electrode plates 44, because the plane of oscillations of ions caused by the AC-field changes upon the ions’ travel along the centerline 46.

Fig. 3a and 3b show a second embodiment of a BIG 42 of the invention, which is very similar to the first embodiment. More precisely, Fig. 3a shows a perspective view and Fig. 3b shows the center line 46 and an exemplary one of the electrode plates 44. The main difference between the first and the second embodiment is that in the second embodiment shown in Fig. 3a and 3b, the radially inner edges 48 of the electrode plates 44 are conically diverging from the center line 46, to thereby establish a conical ion guide volume. It is readily apparent, particularly from Fig. 3b, that this conical ion guide volume can be easily established by forming the shape of the radially inner edge 48 of the respective electrode plates, for example by suitable machining. In the embodiment of Fig. 3a and 3b, the shapes of all eight electrode plates 44 are identical, but this is not necessary. By individually designing the radially inner edges 48 of each of the electrode plates 44, arbitrary, not rotationally symmetric ion guide volumes can be formed, and in particular, volumes that are arranged around a center line that is curved (not shown).

Fig. 4a to 4c show a third embodiment of a BIG 42, which is again similar to the first and second embodiments. The third embodiment likewise comprises 8 electrode plates 44 arranged around the center line 46 (see Fig. 4c), where, similar as in the first embodiment, the radially inner edges 48 are parallel to the center line 46 at an identical distance therefrom. Accordingly, as in the first embodiment, all of the radially inner edges 48 of the electrode plates 44 lie on a cylindrical surface surrounding the center line 46. The difference between the third embodiment of Fig. 4a to 4c and the first embodiment of Fig. 2a to 2c is that in the third embodiment, the electrode plates 44 have a pointed tip formed by an acute angle α between the radially inner edge 48 and an adjacent edge portion 54, as seen in Fig. 4c. The advantage of such a pointed tip is that the BIG 42 can be brought very close to another ion guide, to an ion separation system such as the quadruple mass separator 38 provided in the third pumping chamber 16 shown in Fig. 1, to an ion analysis system, to an ion deposition system, to an ion collision system or to an aperture in a separation wall 20 between adjacent pumping chambers as is shown for the first and second BIGs 42 in Fig. 1, without further structures of the BIG 42 interfering.

A fourth embodiment of a BIG 42 is shown with reference to Fig. 5a to 5e. As can be discerned from these figures, the fourth embodiment can be regarded as an extended version of the first embodiment shown in Fig. 2a to 2c. Like the first embodiment, the fourth embodiment comprises two ring-like elements 50 with slots 52 in which rectangular electrode plates 44 are received. However, for each of the electrode plates 44, an extension element 56 made from metal is provided, which has the shape of a right-angled pyramid with a triangular base. The side 58 of the pyramid that is perpendicular to the triangular base is aligned with the radially inner edge 48 of the corresponding electrode plate 44, as can be seen in Fig. 5b. The function of the pointed extension element 56 is similar to that of the pointed end of the electrode plates 44 shown in the third embodiment of Fig. 4a to 4c. The key advantage of the pyramidal extension elements 56 as compared to the pointed ends of the electrode plates 44 of the third embodiment is that it is structurally more robust.

With reference to Fig. 6a to 6c, a fifth embodiment is shown, which is conceptually and structurally very similar to the third embodiment shown in Fig. 4a to 4c. In the fifth embodiment of Fig. 6a to 6c, the plate electrodes likewise have a pointed tip formed by an acute angle α (see Fig. 6c) between the radially inner edge 48 of the electrode plate 44 and an adjacent edge portion 54. However, while in the third embodiment of Fig. 4a to 4c the shape of the individual plate electrodes 44 was trapezoidal, in the fifth embodiment of Fig. 6a to 6c, the shape of the electrode plates is that of a polygon having five vertices. This shape can be thought of as a rectangular shape with a small triangular extension. This shape allows for a particularly small acute angle α, while at the same time the most part of the electrode plate may still be rectangular, which allows for a particularly easy and precise mounting and provides an improved stability.

With reference to Fig. 7a to 7d, a sixth embodiment of a BIG 42 is shown. Fig. 7a shows a perspective view of the BIG 42 including again 8 electrode plates 44, of which an exemplary one is shown in Fig. 7d. The electrode plate 44 shown in Fig. 7d has a generally rectangular shape, with triangular extensions at its ends each forming an acute angle α between the radially inner edge 48 and an adjacent edge 54. Moreover, at the respective ends and close to the radially outer edge 60, two nose-like protrusions 62 are formed.

Similar to the previous embodiments, the BIG 42 of the sixth embodiment comprises two ring-like elements 50, comprising slots 52 for receiving the plate electrodes 44. A perspective view of one ring-like element 50 is shown in Fig. 7b. As is seen therein, at the radial outer ends of each slot 52, a through hole 64 is formed. The through holes 64 serve to radially fix the electrode plates 44 in the slots 52, for example by injecting glue into these holes 64, or by bending a portion of the electrode plate 44 close to the radially outer edge 60 within the through hole 64. Moreover, on the left end of the BIG 42 of the sixth embodiment as shown in Fig. 7a and 7c, an end ring 66 is provided. As can be seen in in the sectional view of Fig. 7c, the end-ring 66 comprises recesses 68 into which the nose-like protrusion 62 may engage. While in the sectional view of Fig. 7c the recesses 68 appear to be separate, they may in some embodiments also be part of a same annular recess 68.

While difficult to discern with the bare eye in Fig. 7d, a radially inner edge 70 of the nose-like protrusion 62 is slightly inclined. Accordingly, when the nose-like protrusion 62 is inserted into the recess 68 in the end-ring 66, the plate 44 is moved in a radially outer positon, until it acquires a predetermined radial rest position. Accordingly, by attaching the end-ring 66 at one or both of the ends of the electrode plates 44 received in the slots 52 of the ring-like element 50, the electrode plate 44 is moved to and fixed in the pre-determined radial position. The end-ring 66 may for example be attached to the ring-like elements 50 by gluing. If the end-ring 66 is employed, no further fixation of the plate electrodes 44 of the kinds described before, i.e. by means of injecting glue into the holes 64 or bending the radially outer portion of the plate electrode 44 may be necessary.

Finally, with reference to Fig. 8, a seventh embodiment of a BIG 42 is illustrated. As before, the BIG 42 comprises eight electrode plates radially arranged around a center line (not shown in Fig. 8). However, instead of using ring-like elements for holding the plate electrodes 44, in the seventh embodiment shown in Fig. 8, the plate electrodes 44 are embedded within an embedding material 72, such as a molding material which can for example be applied by injection molding. In the embodiment shown, the radially inner edges 48 of the electrode plates 44 are arranged on a cylindrical surface around the center line 46, which is not shown in Fig. 8 for clarity, but corresponds to the symmetry axis of the cylindrical structure shown. A bore is provided in the embedding material 72, which likewise coincides with the cylindrical surface on which the radially inner edges 48 of the electrode plates 44 are arranged. This can for example be achieved by inserting a cylindrical pin having a diameter that is just large enough to simultaneously contact each of the radially inner edges of the electrode plates 44 prior to adding a moldable embedding material 72, and by removing said pin after the moldable material 72 is solidified. In an alternative, the entire space between the electrode plates 44 may be filled with a molding material 72 and may then be removed from the cylindrical area confined by the radially inner edges 48 of the electrode plates 44 by a high precision drilling operation.

Note that in this embodiment, the embedding material 72 extends all the way up to the inner envelope of the radially inner edges 48 of the electrode plates 44. Accordingly, there is a high risk that the embedding material 72 will be hit by stray ions when the BIG 42 is in use. In order to avoid an inadvertent charging of the embedding material 72, in the embodiment shown this embedding material 72 is an intermediate resistivity material having an electrical resistivity of between 10^2 Ohm * cm and 10^{12} Ohm * cm, preferably of between 3 * 10^5 Ohm * cm and 10^9 Ohm * cm. Such intermediate resistivity material can be a plastic material or a ceramic material including or mixed with conductive particles, in particular metal or graphite particles. In an alternative, the embedding material 72 could be a ferrite-based material.

In operation, high-frequency AC voltages are applied to the electrode plates 44 with frequencies on the order of 0.05-20 MHz and amplitudes of some 0.1-100 V. For clarity of illustration, the corresponding high-frequency driving source is omitted in Fig. 1 to 8. A circuit diagram of a suitable driving source is shown in Fig. 9. The driving source comprises a DC voltage source 104, four switches 100 and a control unit 106 for controlling the switching states of the switches 100. Between the switches 100 and the control unit 106 potential separating elements 102 are provided. The RF output voltage is supplied at the terminals 108 and 110. The control unit 106 controls the switches 100 to alternate between two switching states, a first switching state, in which the upper left and the lower right switch 100 are closed and the remaining switches 100 are open, and a second, opposite state, in which the lower left and the upper right switch 100 are closed and the remaining switches 100 are open. In the first switching state, the RF terminal 108 has positive voltage and the RF terminal 110 has negative voltage, while in the second switching state, the voltages are reversed. Accordingly, by alternating between the first and second switching states, under the control of the control unit 106, a square wave RF output voltage at the terminals 108, 110 is provided. Moreover, under the control of the control unit 106, the output RF frequency can be freely adjusted.

Fig. 10 shows a perspective view of a further blade ion guide (BIG) 42 having a set of electrode plates 44 having wedge-like profiles and radially inner edges 48 which are conically converging towards the centerline (not shown in Fig. 10 for clarity) from the left/front end towards the right/back end of Fig. 10. Herein, the angle between the radially inner edges of the electrode plates and the centerline is approximately11,3°. The wide end of the conical ion guide structure facilitates feeding an ion beam into said ion guide 42 at its left/front end as shown in Fig. 10, and is hence less sensitive to slight misalignments of the ion guide 42 with respect to an upstream component. Moreover, the conical structure allows for compressing the ion beam to a lower cross section as it propagates towards the right/back end as shown in Fig. 10. Fig. 11 is a further perspective view of the BIG 42 of Fig. 10, viewed from the left/front end as shown in Fig. 10. As seen in both, Fig. 10 and Fig. 11, the plates 44 are supported by a ring-like holding element 50.

It is seen that in the framework of the present invention, the term “plate” does not require a uniform thickness, but it also covers structures having nonuniform, wedge-like profiles as shown in Fig. 10 and 11, in which the thickness increases in a radially outward direction. In the embodiment shown in Fig. 10 and 11, the electrode plates or “blades” 44 have a specific wedge-like profile, in which – in a cross-section perpendicular to the centerline – the wedge-like profiles form angular sections with gaps in between. This means that at any given circle around the centerline, the ratio between the width of the angular sections in circumferential direction and the width of an adjacent gap is constant, and in the shown embodiment, this ratio is 1:1. This design hence allows for a constant ratio between the blade section and the gap section at the radially inner edge 48 of the wedge-like blades, or in other words, a constant ratio between the thickness 44a of each electrode plate 44 close to its radially inner edge 48 and the inter-plate distance 44b, even if the inner envelope is not constant due to the conical profile of the inner envelope along the longitudinal axis. This allows for optimising this ratio to obtain an optimum current capacity of the ion guide 42 even in case of a conical structure.

A further aspect of the invention addresses the capillary 30 shown in Fig. 1 providing the inlet of the first pumping chamber 12 of the IBD system 10 of Fig. 1. In preferred embodiments, four or more RF electrodes (typically 4-16) are arranged in the wall of this capillary 30, which is an example of the “tube-like device” referred to in the summary of the invention, in order to repel the ions of an ion cloud expanding towards the inner wall of the capillary 30, especially in case of long, narrow capillaries 30. Thus the number if ions leaving the capillary 30 and thereby the intensity of the ion beam may be increased. The usage of long, narrow capillaries 30 reduces the neutral gas load into the first pumping chamber of the IBD system 10 and thus reduces the costs of the most expensive first vacuum pump 22 of the IBD system 10. The capillary 30 may have a straight shape with a circular inner cross section and has an inner surface which is as smooth as possible. In preferred embodiments, there may be electrodes embedded in the wall of the capillary 30 which extend along a longitudinal axis thereof. The ratio of the width of these electrodes versus the gap between the electrodes measured along a line on the inner circumference of the capillary may preferably range between 0.5 and 6.0, more preferably between 0.8 and 4.0. The material between the electrodes may be one of the types of “wall-forming materials” referred to in the summary of the invention. Preferably, RF voltage with opposite polarity is applied to adjacent electrodes with a frequency between 0.1 and 50 MHz, more preferably between 5 and 25 MHz, and most preferably between 10 and 20 MHz, and an amplitude between 0.1 and 500 V, preferably between 5 and 300 V and most preferably between 10 and 100 V. The inner diameter of the capillary preferably ranges from 0.1 to 2.0 mm, more preferably from 0.15 to 1.5 mm and most preferably between 0.2 and 1.0 mm. The length of the capillary may range from 2 to 300 mm, preferably from 10 to 200 mm, and more preferably from 50 to 150 mm.

According to a further preferred embodiment said electrodes are arranged along a closed line on the inner circumference of the capillary essentially perpendicular to the longitudinal axis of the capillary 30. The surface of the electrodes is preferably flush with the material between them to avoid turbulences. The distance between adjacent electrodes along a longitudinal axis of the capillary may be at least below 0.5 times the inner diameter of the capillary 30. The ratio of the width of these electrodes versus the gap between the electrodes measured along a longitudinal axis of the capillary 30 may preferably range between 0.5 and 6.0, more preferably between 0.8 and 4.0. The RF driving voltages and the general dimensions of the inner diameter and the length of the capillary are similar to those of the other embodiment.

Fig. 12 shows a perspective view of a capillary 30, which resembles a specific embodiment of a tube-like device for transferring ions generated by an ion generation source at a first (high) pressure into a chamber with a second (lower) pressure recited in the summary of the invention. As is seen in Fig. 12, the capillary 30 has an inlet 80 for receiving ions generated by an ion generation source 24 (see Fig. 1) at a first pressure, an outlet 82 through which the ions can be emitted towards the chamber with the second pressure, such as the first pumping chamber 12 of Fig. 1, and a wall 84 enclosing a lumen 86 in a tube-like fashion, which lumen 86 extends from the inlet 80 to the outlet 82. As is seen in Fig. 12, a set of electrodes 44 is integrated with said wall 84. Herein, the same reference sign 44 is used as for the electrode plates of the blade ion guides 42 shown above, because these electrodes 44 of the capillary 30 are conceptually similar to those of the BIG 42. Accordingly, any explanations given above regarding technical effects and advantages of the electrode plates 44 with reference to the BIG likewise apply for the capillary 30 as well, without further mention.

While not shown in Fig. 12, the electrodes 44 in operation are connected to an RF voltage source for applying voltages collectively defining an effective potential repelling ions from the wall 84.

Between the electrode plates 44, a wall-forming material 88 is provided, which forms part of the wall 84. The wall-forming material 88 can be any of the materials recited for this purpose in the summary of the invention.

Likewise, the electrodes 44 can be made of any of the preferred materials summarized in the summary of the invention. In some embodiments, the wall-forming material 88 can be a molding material and the electrode plates 44 can be made from metal such as copper, molybdenum, tungsten, nickel, silver, gold, iron or alloys or compounds thereof. Due to the typically small dimensions of the capillary 30, however, the manufacturing by molding can be technically quite demanding.

In particularly preferred embodiments, both the electrode plates 44 and the wall-forming material 88 is therefore a material that is suitable for 3D printing or other additive manufacturing methods, for example a ceramic material like Al2O3, ZrO3 SiC, SiN or combinations thereof. Alternatively, both the wall-forming material 88 as well as the material for the electrode plates 44 may be a plastic material, such as PEEK or composites. In each case, the 3D printable or additively manufacturable base material can be mixed with further components to adjust the conductivity, for example mixed with graphene, carbo nanotubes, carbon fibers, soot, graphite or metal or a ceramic material mixed with metal or metal oxides.

Using 3D printing or other additive manufacturing methods, the capillary 30 as shown in Fig. 12 and the further embodiments shown below can be manufactured with suitable precision and very cost efficiently.

While the lumen 86 can in principle be formed in the process of 3D printing, in preferred embodiments, only a precursor lumen is formed in the 3D printing process, which is then extended and smoothened using a high precision drilling operation to thereby provide for a very smooth inner surface of the wall 84, to thereby allow for an improved gas flow through the capillary 30.

Fig. 13 shows a perspective view of a further embodiment of a capillary 30. Figure 14 shows a partly transparent version of the capillary 30 of Fig. 13, in which the lumen 86 can be particularly well discerned.

The embodiment of Fig. 13 is similar to that in Fig. 12 in that it comprises electrodes 44 that extend in lengthwise direction of the capillary 30, and which are formed by conductive electrode plates 44 which are radially arranged around a center line of the lumen 86. However, in the embodiment of Fig. 13, the electrode plates 44 have a wedge-like profile with a thickness increasing in radially outward direction. As in the case of the blade ion guide (BIG) 42 described above, the term “electrode plate” does not require a uniform thickness, but also allows for plates with a thickness that increases in radially outward direction. In the embodiment shown in Fig. 13 and 14, the wedge-like profile has the shape of circular sections, meaning that the boundaries between the electrode plates 44 and the wall-forming material 88 extends radially away from the center line of the lumen 86.

A further difference from the embodiment of Fig. 12 is that the capillary 30 includes only four electrode plates 44, whereas the capillary 30 of Fig. 12 comprises 16 electrode plates. Note that wedge-like profiles are particularly advantageous for capillaries having smaller numbers of electrode plates 44, such as four or six electrode plates 44.

A further difference of the capillary 30 of Fig. 13 over that from Fig. 12 is that the diameter of the lumen 86 increases towards the inlet 80, thereby forming a funnel-like structure opening towards the inlet 80. As seen in Fig. 13, the radially inner edges of the electrode plates 44 hence diverge from each other in a direction towards the inlet 80. When this capillary 30 is used together with the ESI device 24 shown in Fig. 1, the tip of the emitter (needle) 28 may extend into this funnel region in a manner schematically shown in Fig. 1.

The capillary 30 of Fig. 13 and 14 may likewise be manufactured by 3D printing or other additive manufacturing processes, where again the lumen 86 can be made or reworked by drilling and/or machining operations.

Fig. 15 shows a yet further embodiment of a capillary 30, forming an embodiment of the tube-like device for transferring ions as described in the summary of the invention. The main difference between the embodiment of Fig. 15 to that of Fig. 12 to 14 is that herein, the electrode plates 44 are arranged perpendicularly to the centerline or longitudinal axis of the capillary 30. Each of the electrode plates 44 has an opening which is arranged so that the longitudinal axis extends through its respective opening. Herein, the wall 84 is constituted by alternating ring-like electrodes 44 and annular sealing elements, which are again made from wall-forming material and are referred to with reference sign 88. It is therefore seen that again, the electrodes 44 are integrated with the wall 84, and are separated by the wall-forming material 88.

Also shown in Fig. 15 are lead electrodes 90 to contact every other electrode plate 44 to apply said RF driving voltages thereto, to thereby generate an effective potential repelling ions from the wall enclosing the lumen 86. Note that such lead electrodes are omitted in Fig. 12 to 14 and 16 for clarity. Note that the structure of Fig. 15 is particularly well suitable for 3D printing or any other additive manufacturing method, however, contacting all of the individual electrode plates 44 is more complicated than for example in the embodiment of Fig. 12 and 14.

Fig. 16 shows a yet further variant of a capillary 30, which is again made from adjacent ring-like electrodes 44 with annular sealing elements made from wall-forming material 88 in between. The difference between the embodiment of Fig. 16 to that of Fig. 15 is that an inlet funnel structure is provided, in which the diameter of the lumen 86 increases towards the inlet 80 in a similar manner as shown in Fig. 13 and 14.

Further disclosed herein are the following examples:

1. A tube-like device for transferring ions generated by an ion generation source at a first pressure, in particular atmospheric pressure, into a chamber with a second pressure that is lower than said first pressure, said tube-like device having
    - an inlet for receiving ions generated by said ion generation source at said first pressure,
    - an outlet through which said ions can be emitted towards said chamber with said second pressure,
    - a wall enclosing a lumen in a tube-like fashion, said lumen extending from said inlet to said outlet,

   characterized in that a set of electrodes is integrated with said wall, wherein said electrodes are connected or connectable with an RF voltage source for applying voltages collectively defining an effective potential repelling said ions from said wall.

2. The tube-like device of example 1, wherein said ion generation source is configured for generating charged droplets and/or ions and/or polarizable particles, in particular by

means of generating an aerosol comprising an analyte and a carrier material within a background gas, wherein said carrier material is preferably a volatile fluid, and in particular water and/or other solvents, and wherein said ion generation source is preferably further configured for subsequently removing the carrier material by applying heat and/or a vacuum.

3. The tube-like device of examples 1 or 2, wherein said ion generation source is one of an electrospray ionization source, a physical ionization source, a chemical ionization source, and a cluster source.

4. The tube-like device of example 3, wherein said electrospray ionization source comprises an emitter having an inner diameter between 0.2 µm and 300 µm, preferably between 1 µm and 100 µm, for emitting a liquid of ions in an electrolytic carrier solvent, and a syringe for pushing said liquid towards a tip of said emitter.

5. The tube-like device of one of the preceding examples, wherein said electrodes are separated by, and preferably embedded inside a wall-forming material forming at least part of said wall, wherein said wall-forming material is preferably heat resistant up to at least 200°C and/or resistant against solvents.

6. The tube-like device of example 5 , wherein said electrodes have a radially inner electrode surface facing said lumen, wherein said radially inner electrode surface is flush with the adjacent wall-forming material, or extends over the wall-forming material towards the lumen.

7. The tube-like device of one of examples 5 or 6, wherein said wall-forming material has an electrical resistivity of less than 10^{12} Ohm·cm, preferably of less than 10^{9} Ohm·cm, or has a sheet resistivity of less than 10^{14} Ohm, preferably of less than 10^{10} Ohm on a surface facing said lumen, wherein said sheet resistivity may be an implicit sheet resistivity or a sheet resistivity caused by coating.

8. The tube-like device of one of examples 5 to 7, wherein said wall-forming material is a molding material.

9. The tube-like device of one of examples 5 to 7, wherein at least one, preferably both of said wall-forming material and the material forming said electrodes is suitable for 3D printing or any other additive manufacturing method, and in particular a material comprising one of a ceramic materials like $Al2O3$, $ZrO2$, $Y2O3$, SiC, $Si3N4$, BN, $B4C$,

CaB6, TiB2, ZiB2, Ni, composites or combinations thereof, a plastic material like ABS, PLA, PEEK, CFR-PEEK, nylon, PVDF, PP, POM, PI, SRP, TPI, PSU, PESU, PPSU, PEI, butenidiol-vinylalcoholcopolymer, PET, polyester, PVA, TPC, HTP, TPE, PHA, HIPS, PC, TPU, PETG, PMMA, ASA, polystyrol, PBI, SAN, PVC, PPO, PPM, PAI, PBS, PBT, PA, PEX and copolymers and composites thereof or composites with other materials such as ceramics, possibly mixed with graphene, carbon nanotubes, carbon fibers, soot, graphite or metal or a ceramic material mixed with metal or metal oxides.

10. The tube-like device of one of the preceding examples, wherein an inner diameter of the lumen is, at least in some portions thereof, between 0.1 and 2.0 mm, preferably between 0.15 and 1.5 mm and most preferably between 0.2 and 1.0 mm.

11. The tube-like device of one of the preceding examples, wherein the distance between adjacent electrodes is, at least in some portions of the tube-like device, less than 0.5 times the inner diameter of the lumen, preferably less than 0.3 times the inner diameter of the lumen.

12. The tube-like device of one of the preceding examples, wherein said electrodes are connected to an RF driving source configured to drive adjacent two electrode plates with voltages of opposite polarity,
wherein the amplitude of the driving voltage is preferably between 0.1 and 500 V, more preferably between 5 and 300 V and most preferably between 10 and 100 V,
wherein the frequency is preferably between 0.1 and 50 MHz, more preferably between 5 and 25 MHz, and most preferably between 10 and 20 MHz, wherein the frequency is preferably freely adjustable, wherein said RF driving source is preferably configured to drive the electrodes with an RF square wave signal or a superposition of RF square wave signals, preferably with a selectable duty cycle.

13. The tube-like device of one of the preceding examples, wherein the electrodes are made from copper, molybdenum, tungsten, nickel, silver, gold, iron or alloys or compounds thereof or have a coating of any of these materials.

14. The tube-like device of one of the preceding examples, wherein the diameter of said lumen is varied along the length thereof, wherein particular a funnel structure is formed adjacent to one or both of the inlet and outlet.

15. The tube-like device of one of the preceding examples, wherein said set of electrodes comprises electrodes extending in lengthwise direction of the tube-like device.

16. The tube-like device of example 15, wherein said electrodes are straight or helically wound around said lumen.

17. The tube-like device of example 15 or 16, wherein said electrodes are formed by conductive electrode plates which are radially arranged around a centerline of said lumen.

18. The tube-like device of example 17, wherein for each electrode plate, there exists a radius vector pointing radially outward from said centerline and lying within said electrode plate.

19. The tube-like device of example 17 or 18, wherein said centerline is a straight line defining a longitudinal axis of said lumen.

20. The tube-like device of example 17 or 18, wherein said centerline is a curved line.

21. The tube-like device of one of examples 17 to 20, wherein in each section plane along the length of and perpendicular to the centerline, the distances of the radially inner edges of the electrode plates from the centerline is identical, or varies by less than 15%, preferably by less than 10%.

22. The tube-like device of one of example 17 to 21, wherein the electrode plates have one of
    - a uniform thickness, and
    - a wedge-like profile with a thickness increasing in radially outward direction.

23. The tube-like device of example 22, wherein in a cross-section perpendicular to centerline of the lumen, the wedge-like profiles form angular sections with gaps in between, wherein said gaps are at least partially filled with said wall-forming material, wherein at any given circle around and along the centerline, the ratio between the width of the angular sections in circumferential direction and the width of an adjacent gap is between 0.5 and 6.0, preferably between 0.8 and 4.0.

24. The tube-like device of example 22, wherein at any given circle around and along the centerline, the ratio between the width of the wedge-like electrode plate in circumferential direction and the width of the adjacent gap is identical, or deviates from the average ratio by less than 50%, preferably by less than 20%.

25. The tube-like device of one of examples 15 to 24, wherein in a portion adjacent to the inlet, the radially inner edges of the electrode plates are diverging from each other in a direction towards the inlet, to thereby form a funnel like structure opening towards the inlet, and/or
wherein in a portion adjacent to the outlet, the radially inner edges of the electrode plates are diverging from each other in a direction towards the outlet, to thereby form a funnel like structure opening towards the outlet,
wherein the opening angle of the respective funnel structure towards the inlet is preferably between 5° and 180°, more preferably between 15° and 120°, and most preferably between 45° and 90°,
wherein the opening angle of the respective funnel structure towards the outlet is preferably between 5° and 90°, more preferably between 20° and 60°, and most preferably between 30° and 55°.

26. The tube-like device of one of examples 15 to 25, wherein the number of electrodes extending in lengthwise direction is 4, 6, 8, 10, 12, 14 or 16.

27. The tube-like device of one of examples 17 to 26, wherein the ratio of the thickness of each electrode plate close to its radially inner edge and the inter-plate distance, at any given position along the centerline, is between 0.5 and 6.0, preferably between 0.8 and 4.0, wherein the inter-plate distance is defined as the distance between the radially inner edges of adjacent electrode plates at a given position along said centerline.

28. The tube-like device according to one of examples 1 to 14, wherein said lumen extends along a longitudinal axis of said device, wherein said set of electrodes comprises a plurality of electrode plates which are arranged perpendicularly to the longitudinal axis, each electrode plate having an opening and being arranged such that said longitudinal axis extends through its respective opening.

29. The tube-like device according to example 28, in which annular sealing elements are arranged between adjacent electrode plates, said annular sealing elements forming, together with radially inner edges of said openings, said wall enclosing said lumen in a tube-like fashion.

30. The tube-like device according to example 29, wherein some or all of said sealing elements are coated at least on a surface facing said lumen with a coating suitable for draining the charge of stray ions to thereby avoid static charging of said sealing elements by stray ions.

31. The tube-like device of example 30, wherein said coating is a metal film having a thickness of 30 to 1000 nm, or a paste containing glass and metal oxides, wherein said paste preferably has a thickness of 5 to 1000 µm.

32. The tube-like device of one of examples 29 to 31, wherein said sealing elements are formed by annular discs, wherein said annular discs preferably serve as spacers to adjust the distance between adjacent electrode plates.

33. An assembly for generating ions at a first pressure and transferring the generated ions into a chamber with a second pressure that is lower than said first pressure, wherein said assembly comprises an ion generation source, in particular an ion source as defined in one of examples 2 to 4, and a tube-like device according to one of the preceding examples.

34. A method of manufacturing a tube-like device according to one of examples 1 to 32, wherein said set of electrodes and the remainder of the wall are manufactured by additive manufacturing methods, also known as 3D printing such as powder, filament or fluid methods, for example selective laser sintering (SLS) or selective laser melting (SLM) or electron beam melting (EBM) or stereolithography (STL, STA) or digital light processing (DLP) or fused filament fabrication (FFF) or fused depositoin modelling (FDM) or multi jet modeling (MJM, Polyjet) or film transfer imaging (FTI).

35. The method of example 34, further comprising a step of drilling or machining the lumen through the 3D printed or additively manufactured device, wherein preferably, a precursor lumen is provided by the 3D printing or by the additive manufacturing method, and the machining or drilling is carried out to provide for a smoothened wall confining the lumen.

36. A method of transferring ions generated by an ion generation source at a first pressure, in particular atmospheric pressure, into a chamber with a second pressure that is lower than said first pressure, said method comprising
    - receiving ions generated by said ion generation source at said first pressure at an inlet of a tube-like device according to one examples 1 to 32,
    - guiding said ions through said tube-like device and
    - emitting said ions to said chamber with the second pressure through said outlet of said tube-like device,

- wherein RF voltages are applied to the electrodes of said tube-like device such as to generate an effective potential repelling said ions from the wall of said tube-like device.

37. The method of example 36, wherein said method further comprises a step of generating ions using said ion generation source, in particular by means of electrospray ionization, physical ionization, chemical ionization or from a cluster source.

Although a preferred exemplary embodiment is shown and specified in detail in the drawings and the preceding specification, these should be viewed as purely exemplary and not as limiting the invention. It is noted in this regard that only the preferred exemplary embodiment is shown and specified, and all variations and modifications should be protected that presently or in the future lie within the scope of protection of the invention as defined in the claims.

10	IBD system
12	first pumping chamber
14	second pumping chamber
16	third pumping chamber
18	fourth pumping chamber
20	separation wall
22	vacuum pump
24	electrospray ionization (ESI) device
26	substrate
28	needle
30	heated capillary
32	combined tunnel and funnel
34	aperture
36	wire based ion guide (WIG)
38	quadrupole mass separator
40	rod electrode
42	blade ion guide (BIG)
44	electrode plate
46	centerline of BIG
48	radially inner edge of electrode plate 44
50	ring-like holding element
52	slot in ring-like holding element 50
54	adjacent edge forming acute angle with radially inner edge 48
56	pyramidal extension
58	edge of pyramidal extension 56
60	radially outer edge of electrode plate 44
62	nose-like protrusion
64	hole in ring-like holding element
66	endring
68	recess in endring 66
70	radially inner edge of nose-like protrusion 62
72	embedding material
80	inlet
82	outlet
84	wall
86	lumen
88	wall-forming material
90	lead

100	switch
102	potential separating element
104	DC voltage source
106	control unit
108	RF terminal
110	RF terminal

Claims

1. An ion guide (42) for guiding an ion beam along an ion path, said ion guide having a centerline (46) corresponding to said ion path, and a plurality of electrodes extending along said centerline, characterized in that

   said electrodes are formed by conductive electrode plates (44) which are radially arranged around said centerline (46),

   wherein each of said electrode plates (44) has a radially inner edge (48) that is closest to the centerline (46), and wherein an inner envelope of the radially inner edges (48) defines an ion guide volume,

   wherein said electrode plates (44) are connected or connectable with an RF voltage source for applying voltages collectively confining ions within said ion guide volume,

   characterized in that the radially inner edges (48) of the electrode plates (44) are, at least in a section along the length of the ion guide (42), conically converging or diverging from the centerline (46), wherein the average angle between the radially inner edges (48) of the electrode plates (44) and the centerline (46) within said section is less than 45° and is 0.1° or more,

   wherein the electrode plates (44) have a wedge-like profile with a thickness increasing in radially outward direction, and

   wherein the ratio of the thickness of each electrode plate (44) close to its radially inner edge and the inter-plate distance, at any given position along the centerline (46), is between 0.5 and 6.0, wherein the inter-plate distance is defined as the distance between the radially inner edges (48) of adjacent electrode plates (44) at a given position along said centerline (46).

2. The ion guide (42) of claim 1, wherein for each electrode plate (44), there exists a radius vector pointing radially outward from said centerline (46) and lying within said electrode plate (44).

3. The ion guide (42) of claim 1 or 2, wherein said centerline (46) is a straight line defining a longitudinal axis of said ion guide.

4. The ion guide (42) of claim 1 or 2, wherein said centerline (46) is a curved line.

5. The ion guide (42) of one of the preceding claims, wherein in each section plane along the length of and perpendicular to the centerline (46), the distances of the radially inner edges of the electrode plates from the centerline (46) is identical, or varies by less than 15%, preferably by less than 10%.

6. The ion guide (42) of one of the preceding claims, further comprising a holding structure (50, 72) for holding the electrode plates, wherein a portion of said holding structure (50, 72), if any, which is separated from said inner envelope by less than the local inter-plate distance, preferably by less than twice the local inter-plate distance, and most preferably by less than three times the local inter-plate distance is made from a material having an electrical resistivity of less than 10^{12} Ohm·cm, preferably of less than 10^{9} Ohm·cm, or has a sheet resistivity of less than 10^{14} Ohm, preferably of less than 10^{10} Ohm on a surface facing said ion guide volume (128), wherein the local inter-plate distance is defined as the distance between the radially inner edges (48) of adjacent electrode plates (44) at a given axial position.

7. The ion guide (42) of claim 6, wherein the holding structure comprises ring-like elements (50) having slots (52) in which the electrode plates (44) are received.

8. The ion guide (42) of one of the preceding claims, wherein in a cross-section perpendicular to the centerline (46), the wedge-like profiles form angular sections with gaps in between, wherein at any given circle around and along the centerline (46), the ratio between the width of the angular sections in circumferential direction and the width of an adjacent gap is constant and is between 0.5 and 6.0, preferably between 0.8 and 4.0.

9. The ion guide (42) of one of the preceding claims, wherein the electrode plates (44) have a pointed tip formed by an acute angle between the radially inner edge (48) of each electrode plate (44) and an adjacent edge portion (54) of said electrode plate (44) on at least one of the longitudinal ends of the ion guide, wherein the acute angle is 70° or less, preferably 50° or less, and most preferably 30° or less.

10. The ion guide (42) of one of the preceding claims, wherein the average angle between the radially inner edges (48) of the electrode plates (44) and the centerline (46) within said section is less than 5°, and preferably less than 1°, and is 0.2° or more, and preferably 0.5° or more.

11. The ion guide (42) of one of the preceding claims, wherein the number of electrode plates (44) is 6 or more, preferably 8 or more, more preferably 10 or more, and most preferably 12 or more.

12. The ion guide (42) of one of the preceding claims, wherein the electrode plates (44) are made from copper, molybdenum, tungsten, nickel, silver, gold, iron or alloys or compounds thereof or have a coating of these materials.

13. The ion guide (42) of one of the preceding claims, wherein the thickness of each electrode plate (44) close to the radially inner edges (48) is 5.0 mm or less, preferably 1.0 mm or less, and more preferably 0.1 mm or less.

14. The ion guide (42) of one of the preceding claims, wherein the ratio of the thickness of each electrode plate (44) close to its radially inner edge and the inter-plate distance, at any given position along the centerline (46), is between 0.8 and 4.0.

15. The ion guide (42) of one of the preceding claims, wherein the inner envelope is confined, in each section perpendicular to said centerline, by a polygon having as many vertices as there are electrode plates (44), and wherein each of the vertices is located on a radially inner edge (48) of a corresponding one of the electrode plates (44), wherein the cross-section area of this inner envelope at the narrowest position along the centerline (46) is less than or equal to 200 mm^2, preferably less than or equal to 20 mm^2, and most preferably less than or equal to 2.0 mm^2; and is larger than or equal to 0.1 mm^2, preferably larger than or equal to 0.2 mm^2, and most preferably larger than or equal to 0.5 mm^2.

16. The ion guide (42) of one of the preceding claims, wherein said electrode plates (44) are connected to an RF driving source configured to drive adjacent two electrode plates with voltages of opposite polarity and freely adjustable radiofrequency.

17. The ion guide (42) of claim 16, wherein said RF driving source is configured to drive the electrode plates (44) with an RF square wave signal, or a superposition of RF square wave signals, preferably with a selectable duty cycle.

18. The ion guide (42) of one of the preceding claims, wherein at least some of the electrode plates (44) are segmented, having conductive portions separated by intermediate portions of lower conductivity, in particular insulating portions, and wherein different DC voltages are applied to different conductive portions, to thereby generate an electric field along the length of the electrode plate (44).

19. The ion guide (42) of one of the preceding claims, wherein said ion guide (42) is part of an ion beam deposition system (10), in which an ion beam is guided through a plurality of pumping chambers (12-18) of decreasing pressure, wherein adjacent pumping chambers (12-18) are divided by separation walls (20) having an aperture for the ion beam to pass through.

20. An ion guide assembly comprising two or more ion guides (42) of one of the preceding claims, wherein said two or more ion guides (42) are arranged with their centerlines (46) aligned with each other at the respective adjacent ends of said at least two ion guides (42), wherein said adjacent ends of the at least two ion guides (42) are separated in a direction along said centerlines (46) preferably by at least 0.01 mm and preferably by less than three times, more preferably by less than two times and most preferably by less than the square root of the cross-section area of the inner envelope of the corresponding end of one of the adjacent the ion guides (42).

21. The ion guide assembly of claim 20, wherein adjacent ones of said two or more ion guides (42) are arranged in adjacent pumping chambers (12-18) which are separated by means of a separation wall (20), wherein an aperture is provided in the separation wall (20) permitting ions guided by said adjacent ion guides to traverse from one pumping chamber (12-18) into the other.

22. The ion guide assembly of claim 21, wherein the diameter of said aperture in the separation wall (20) is 4.0 mm or less, preferably 3.0 mm or less, and more preferably 2.0 mm or less.

23. An ion guide assembly comprising
   - an ion guide (42) of one claims 9 to 18 having a pointed tip, and
   - a further ion processing system selected from a group consisting of another ion guide (42), an ion separation system, an ion analysis system (38), an ion deposition system and an ion collision system,

wherein said pointed tip is located adjacent to an entrance or exit of said further ion processing system.

24. An ion beam deposition system (10) comprising at least one ion guide (42) or ion guide assembly of one of the preceding claims.

25. A method of guiding an ion beam along an ion path, said ion guide (42) having a centerline (46) corresponding to said ion path, and a plurality of electrodes extending along said centerline (46), characterized in that

said electrodes are formed by conductive electrode plates (44) which are radially arranged around said centerline (46),

wherein each of said electrode plates (44) has a radially inner edge (48) that is closest to the centerline (46), and wherein an inner envelope of the radially inner edges (48) defines an ion guide volume,

wherein each adjacent two electrode plates (44) are driven with RF voltages of opposite polarity, in particular with an RF square wave drive signal, wherein the method preferably further comprises a step of adjusting the RF frequency and the voltage amplitude of the drive signal depending on the type of ions to be guided by said ion guide (42).

26. The method of claim 25, wherein said ion guide is an ion guide of one of claims 1 to 19.

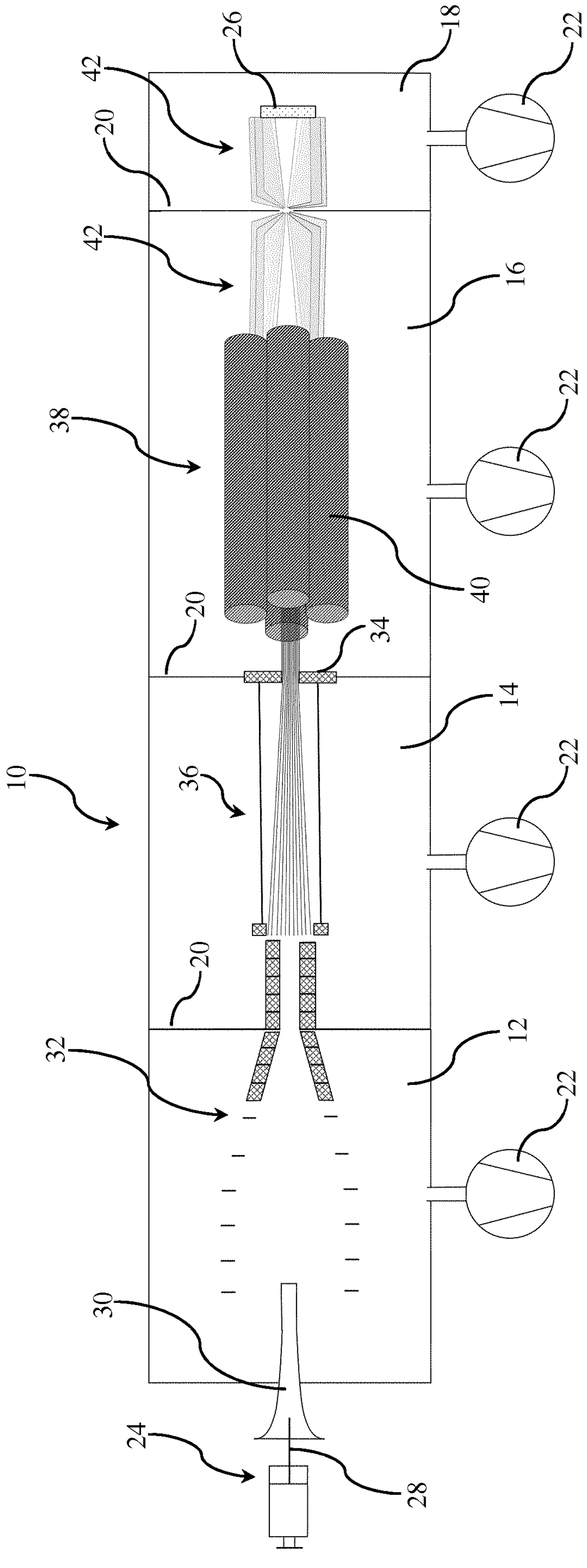

Fig. 1

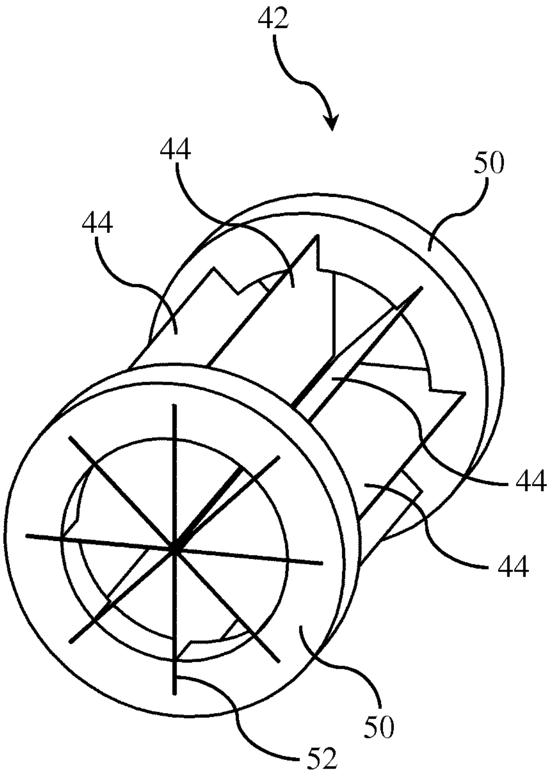

Fig. 2a

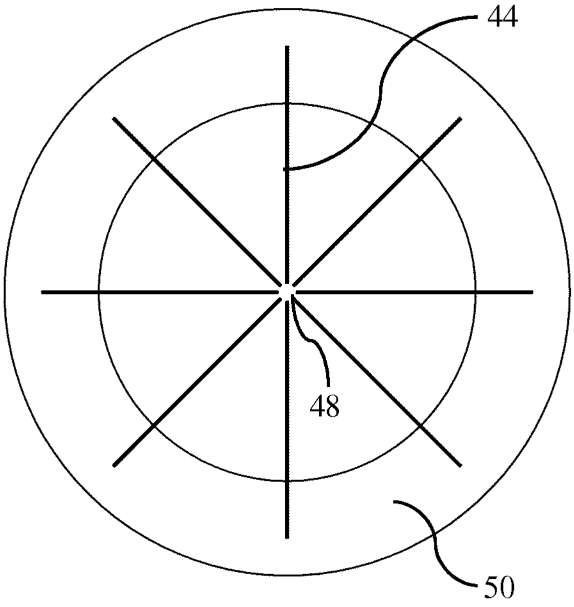

Fig. 2b

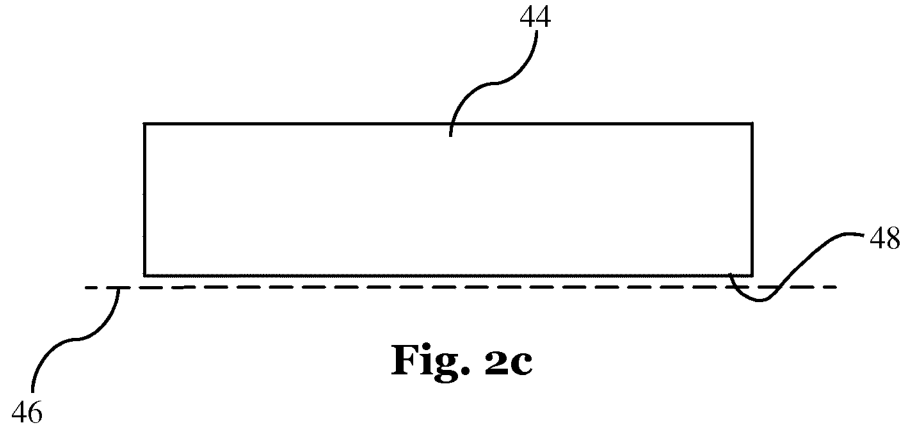

Fig. 2c

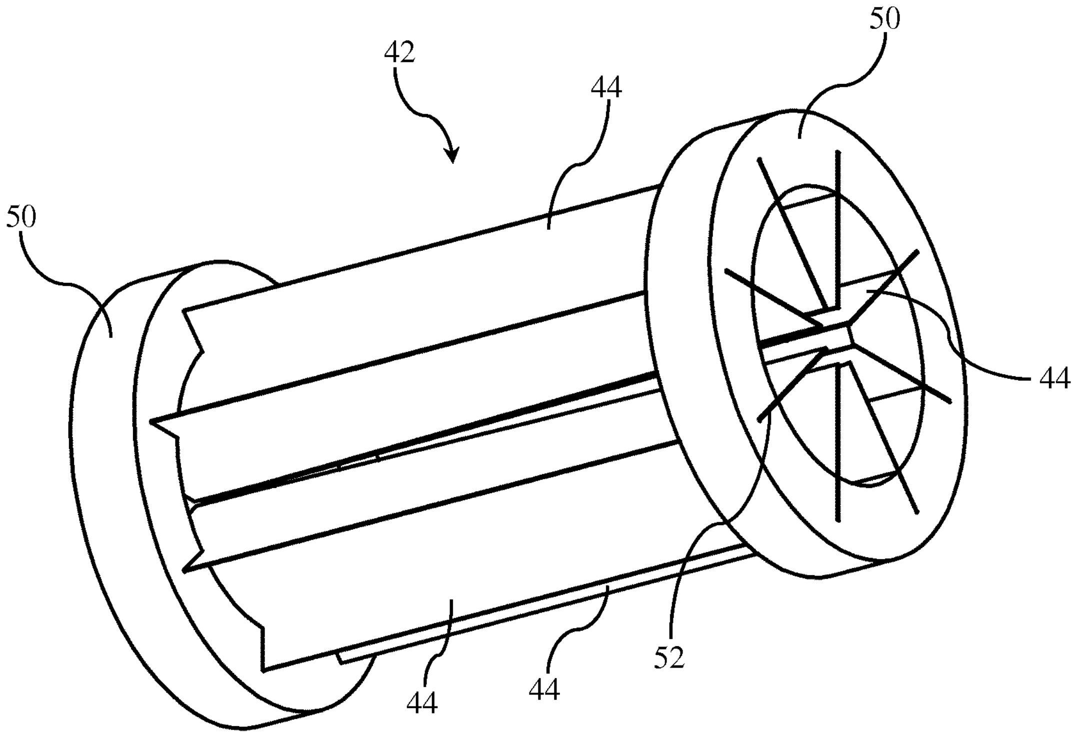

Fig. 3a

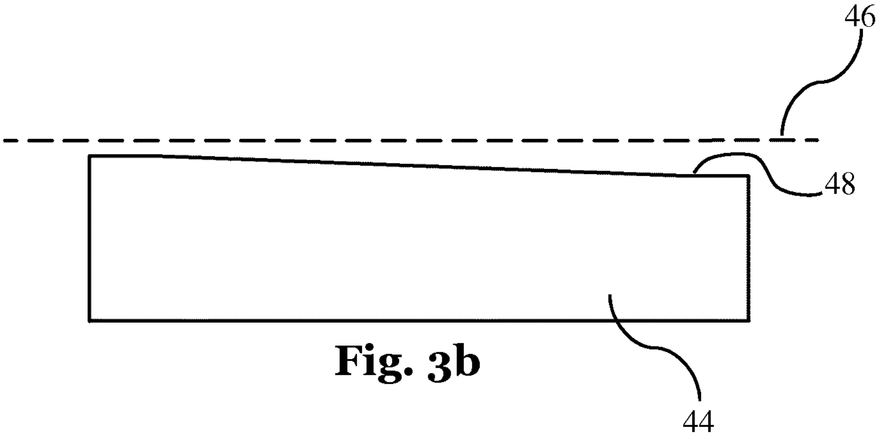

Fig. 3b

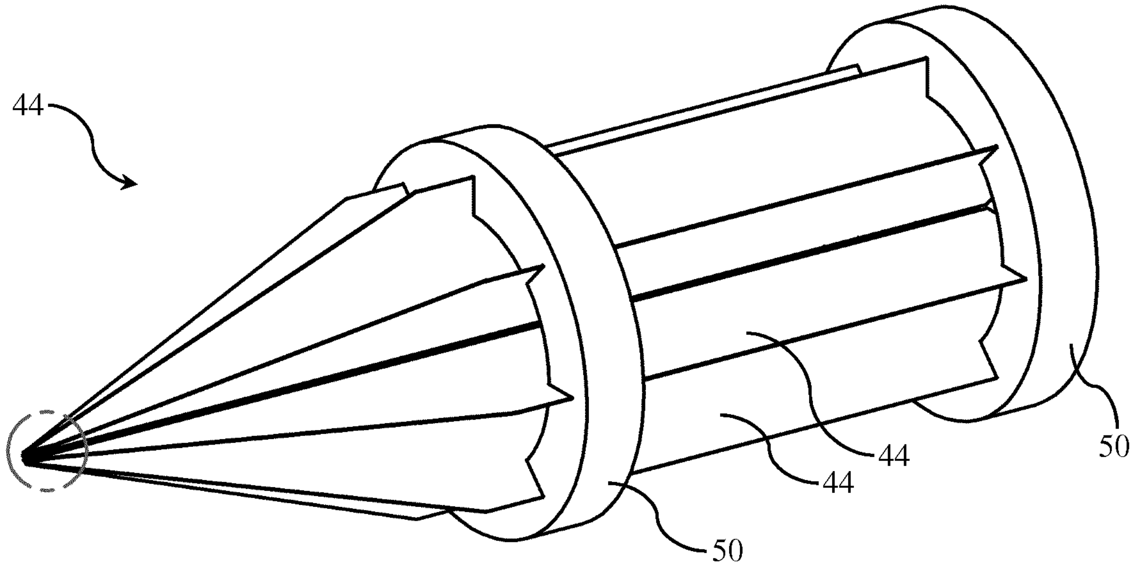

Fig. 4a

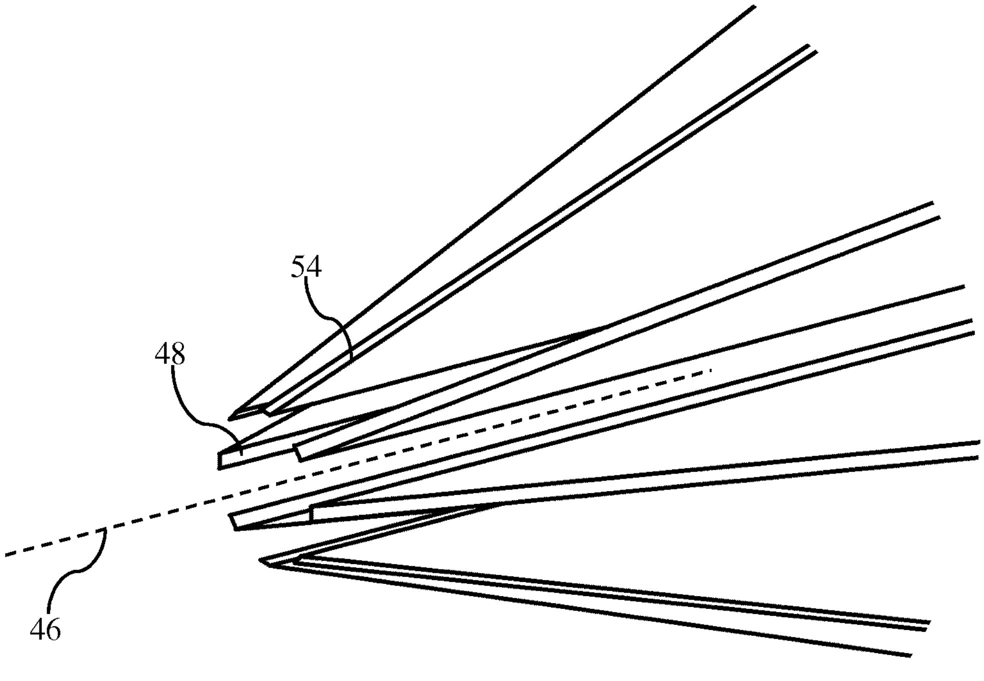

Fig. 4b

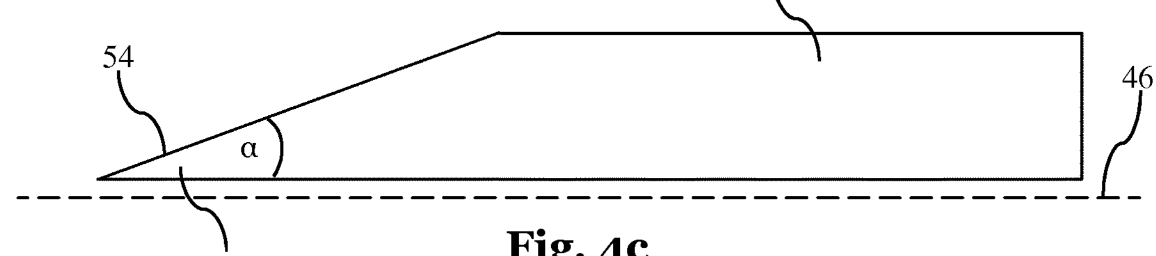

Fig. 4c

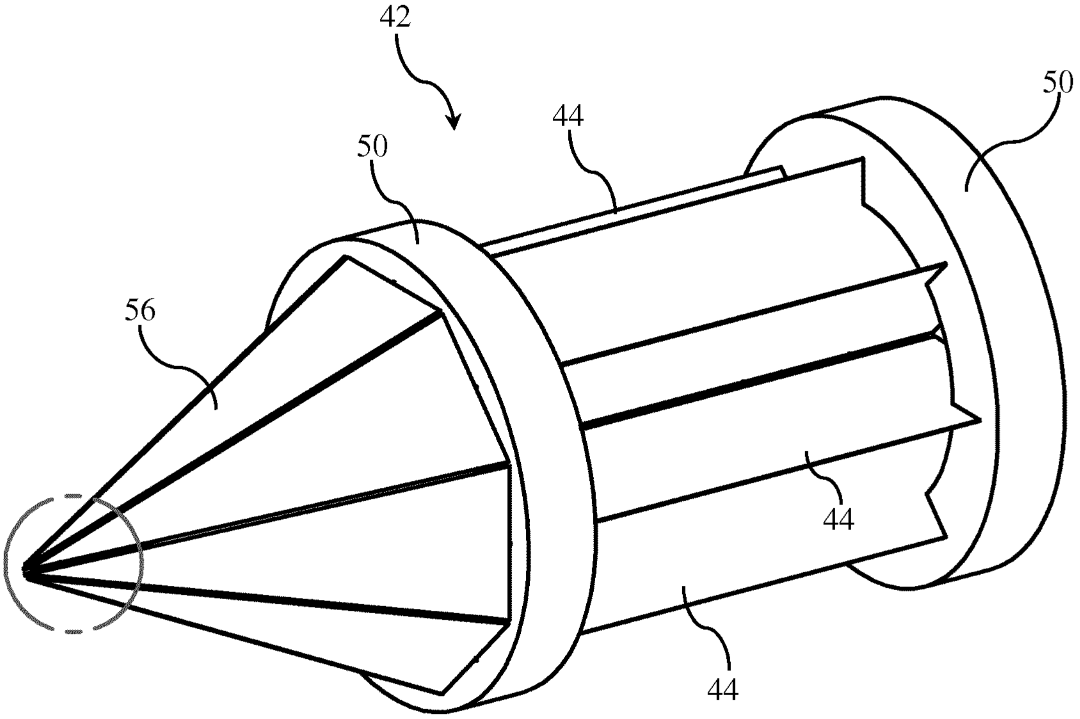

Fig. 5a

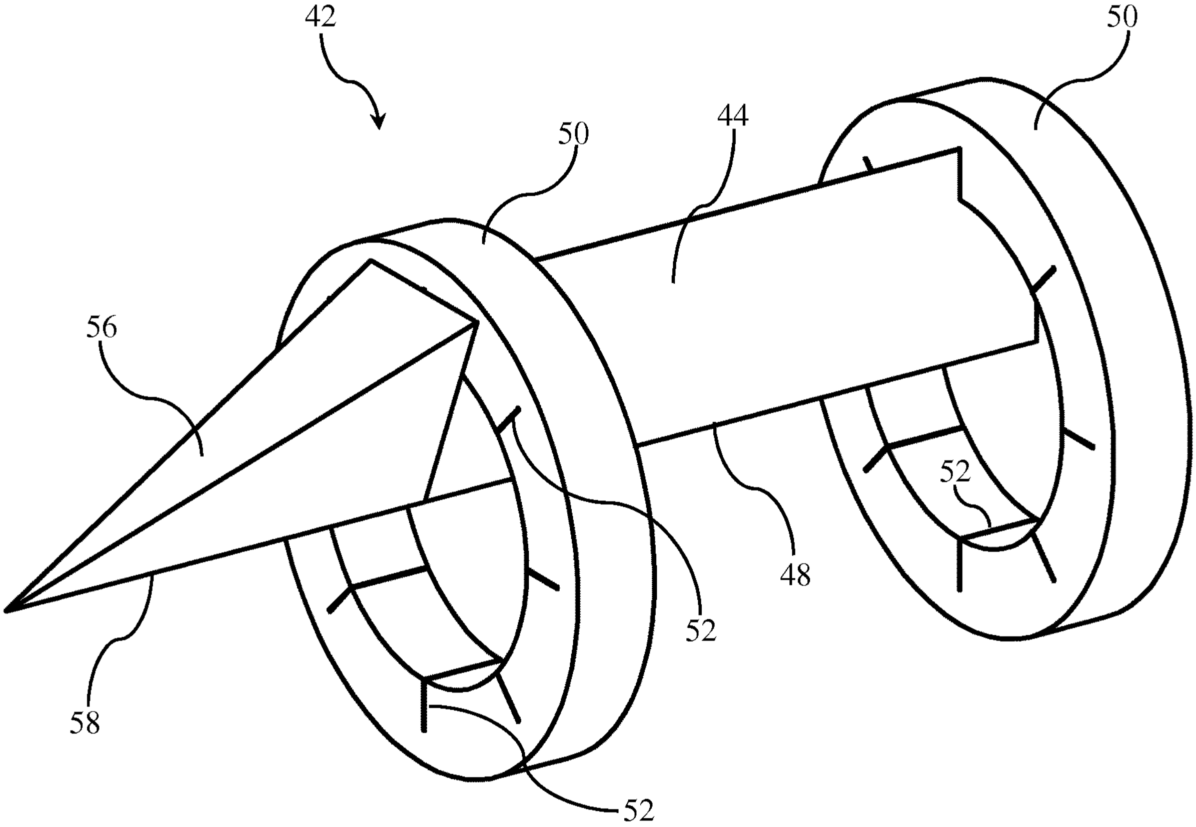

Fig. 5b

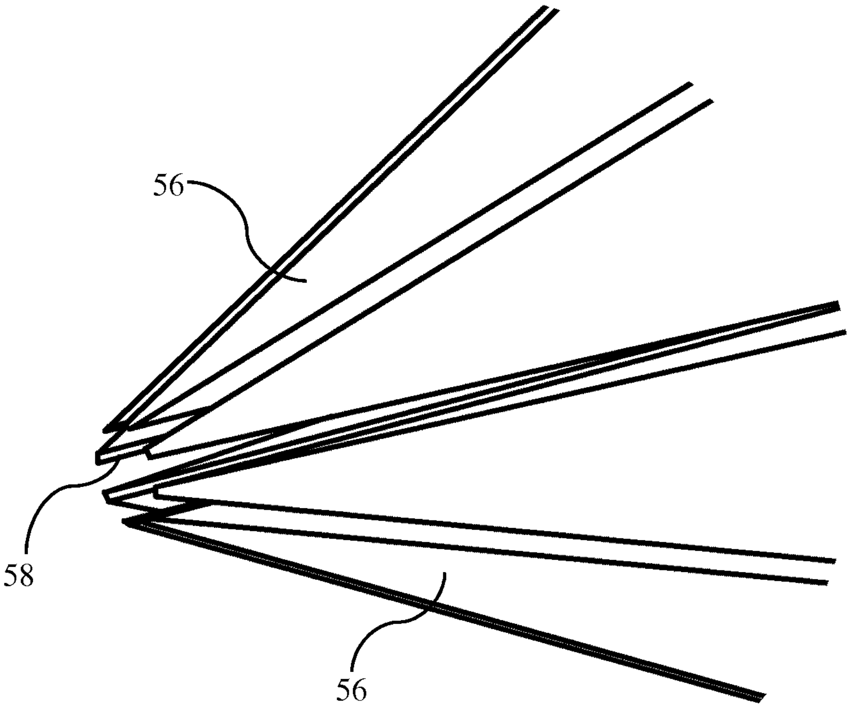

Fig. 5c

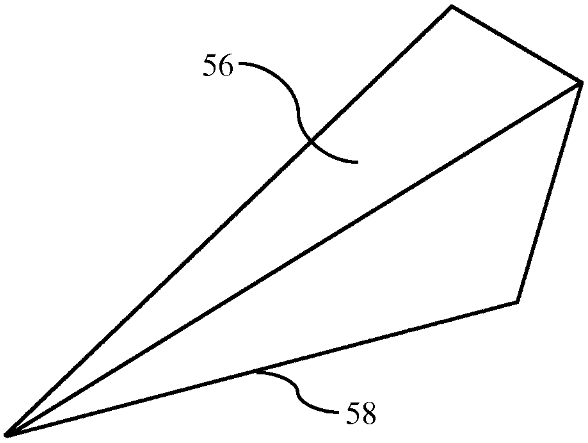

Fig. 5d

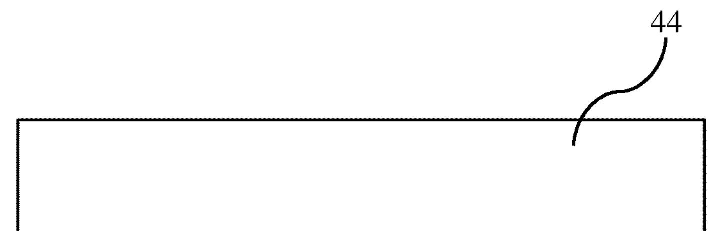

Fig. 5e

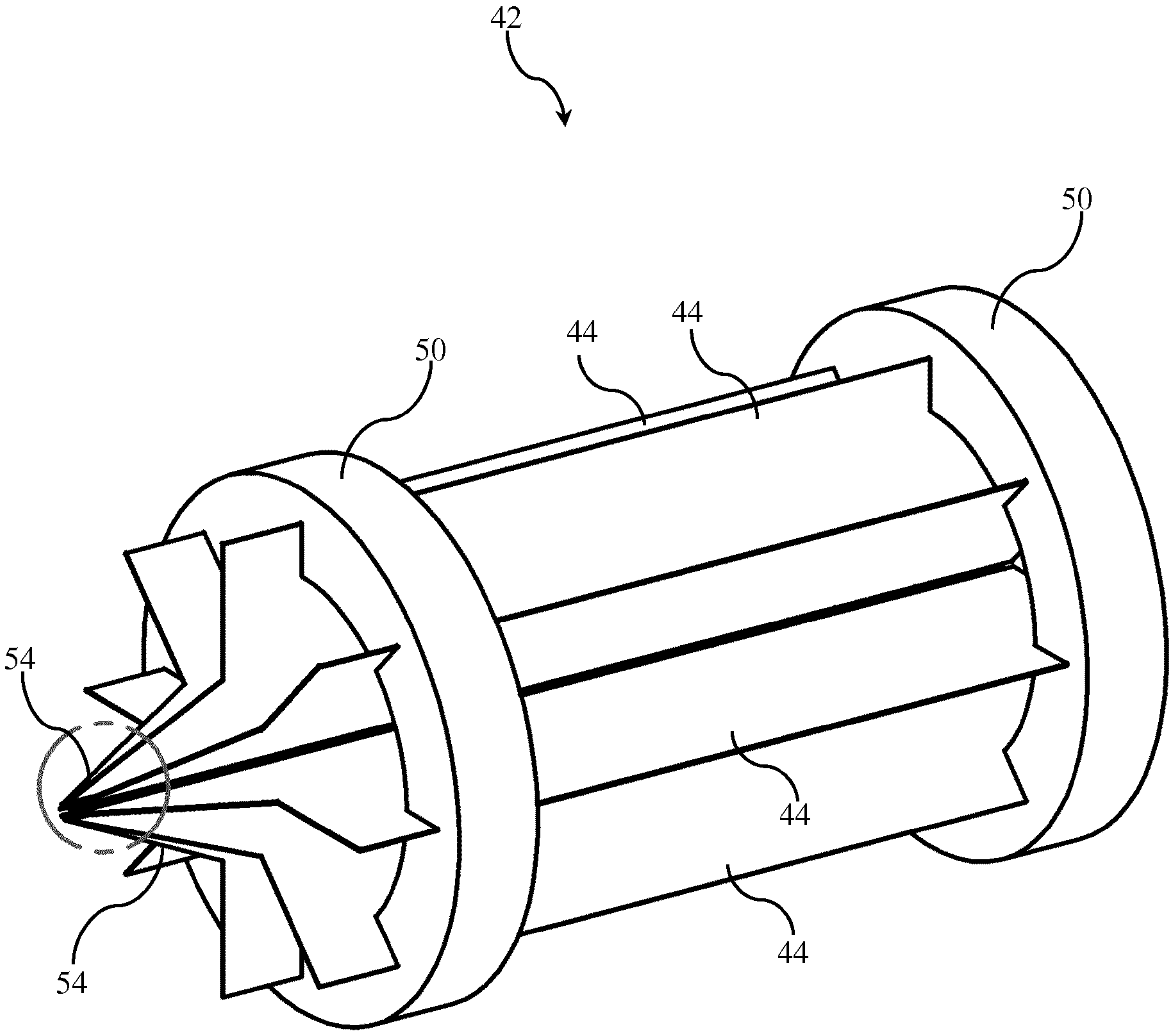

Fig. 6a

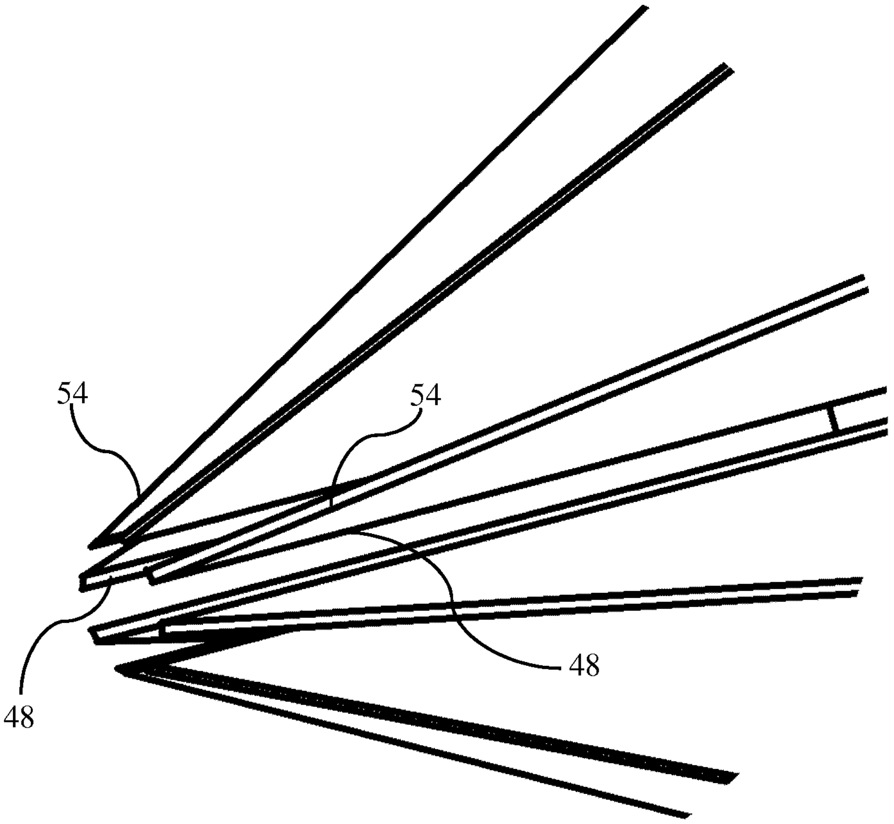

Fig. 6b

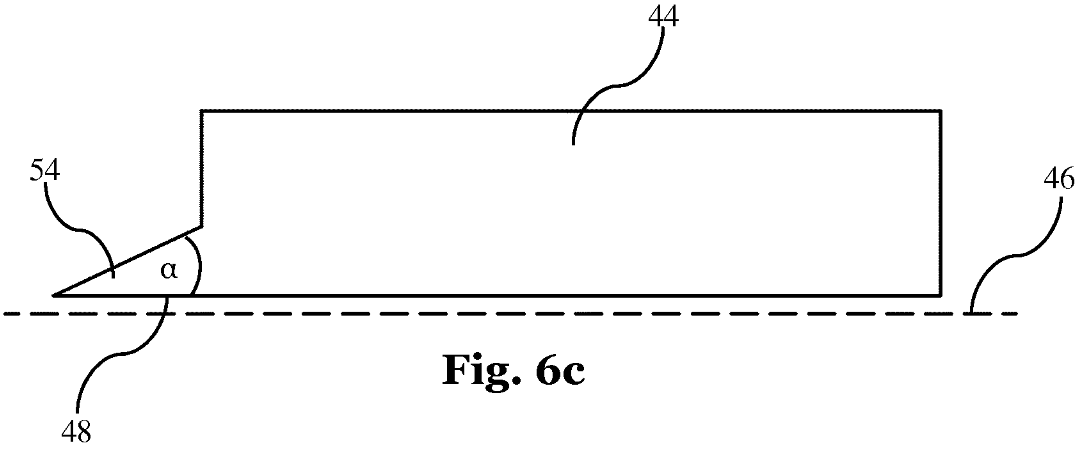

Fig. 6c

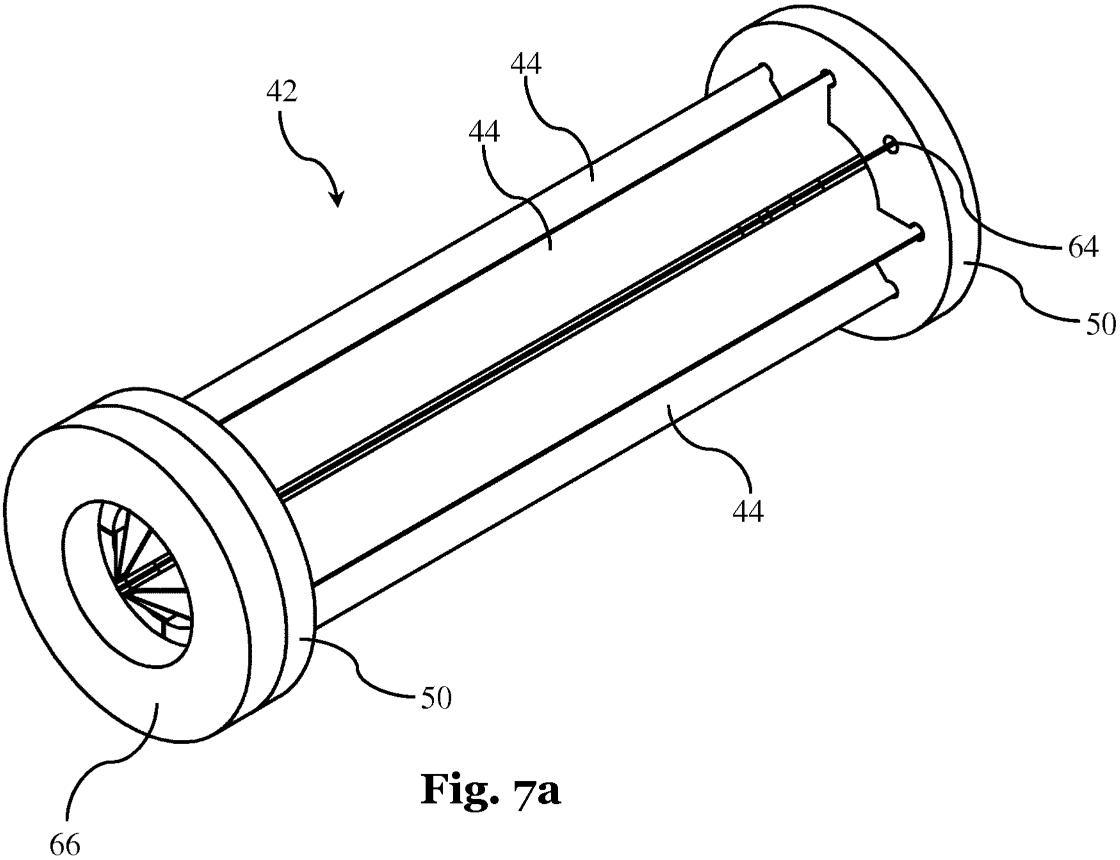

Fig. 7a

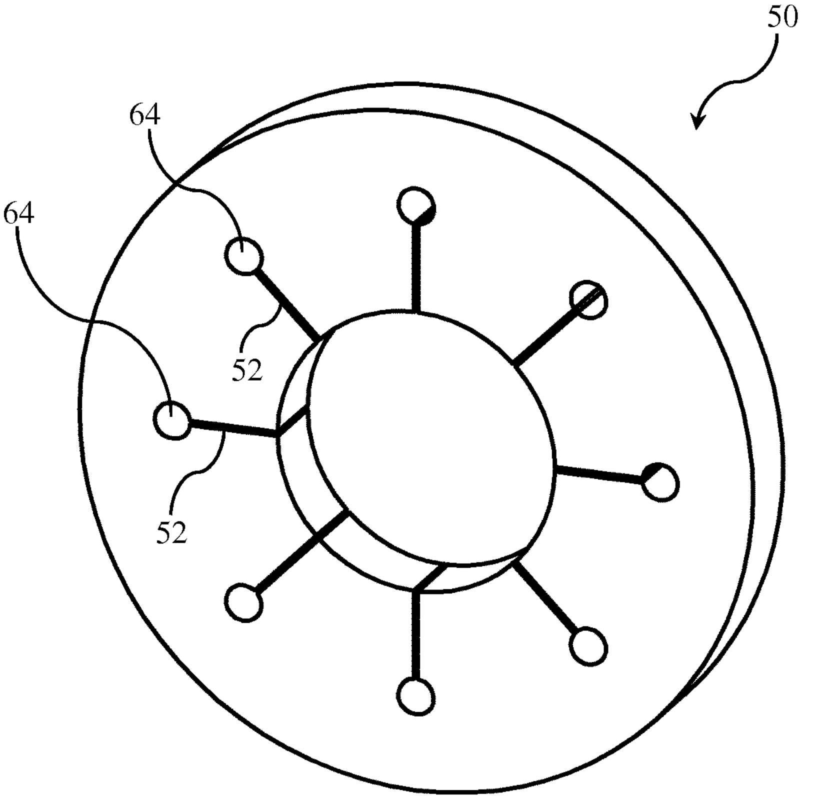

Fig. 7b

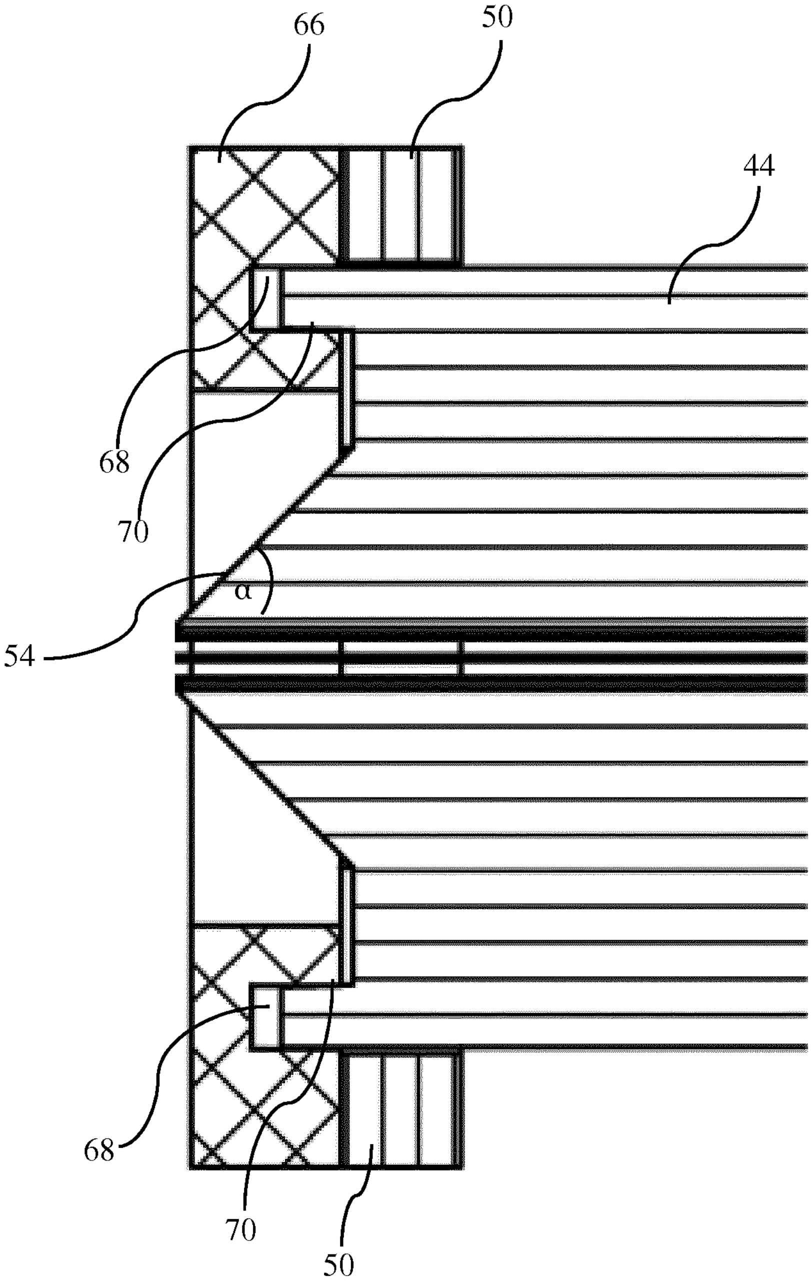

Fig. 7c

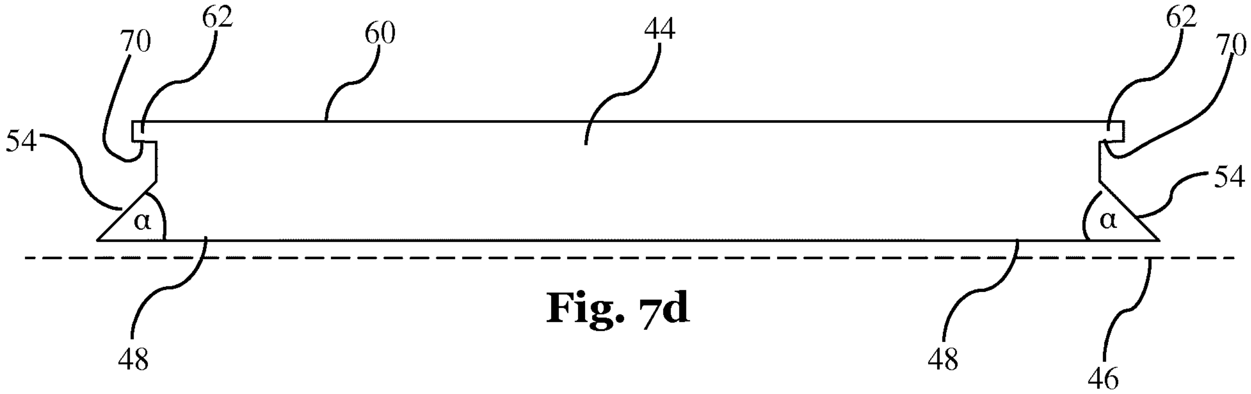

Fig. 7d

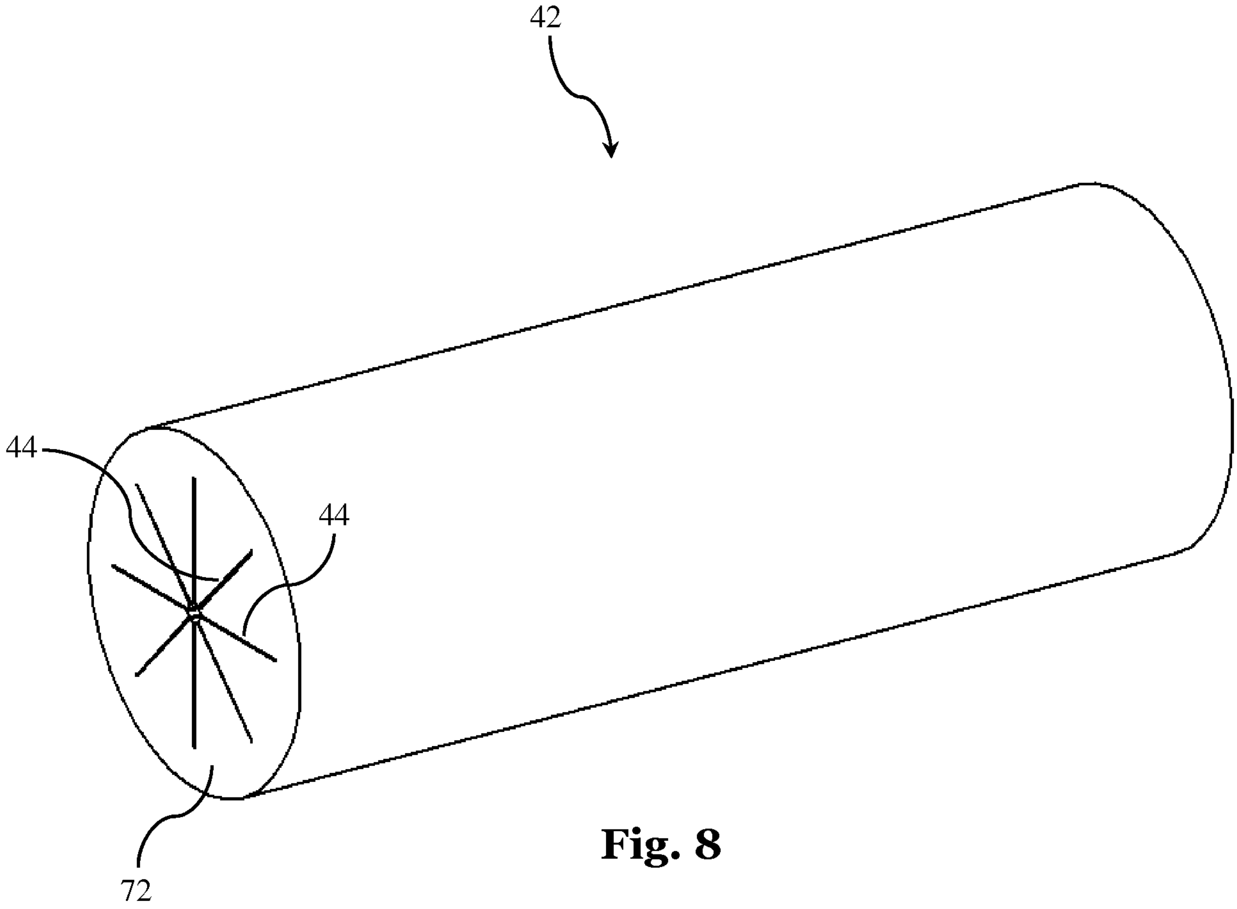

Fig. 8

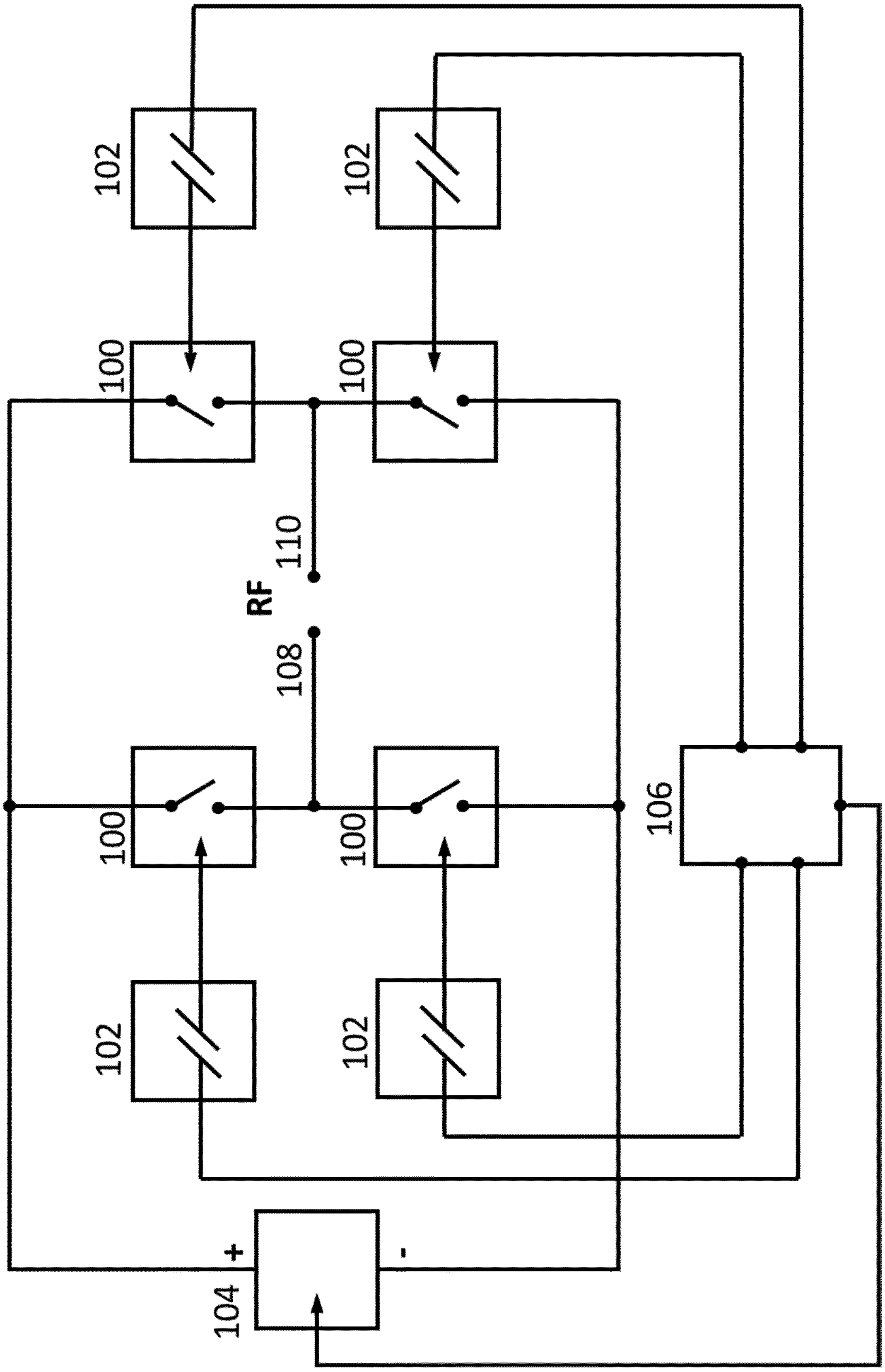

Fig. 9

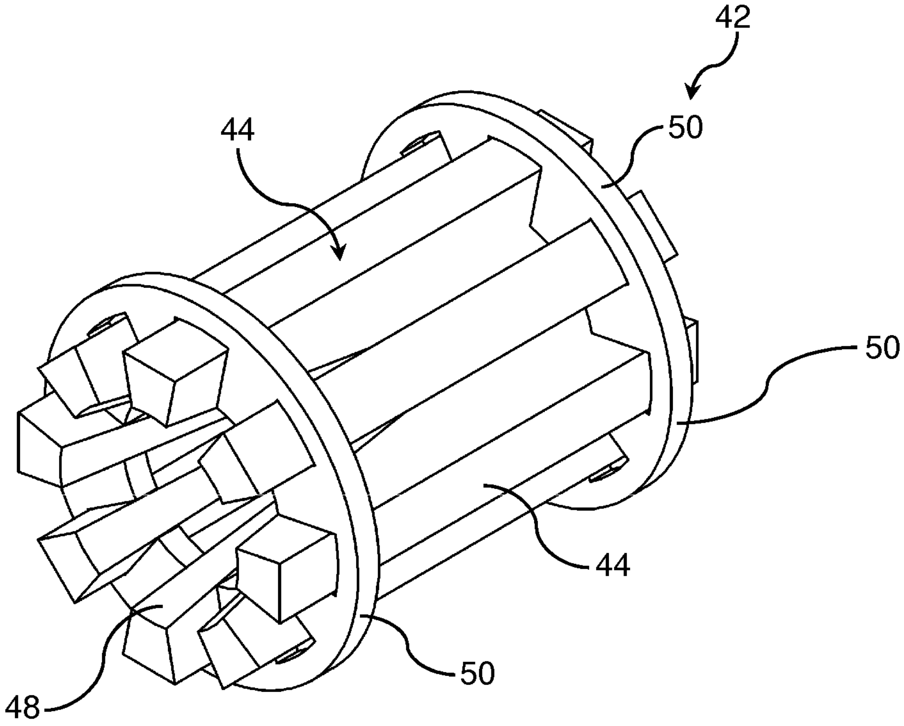

Fig. 10

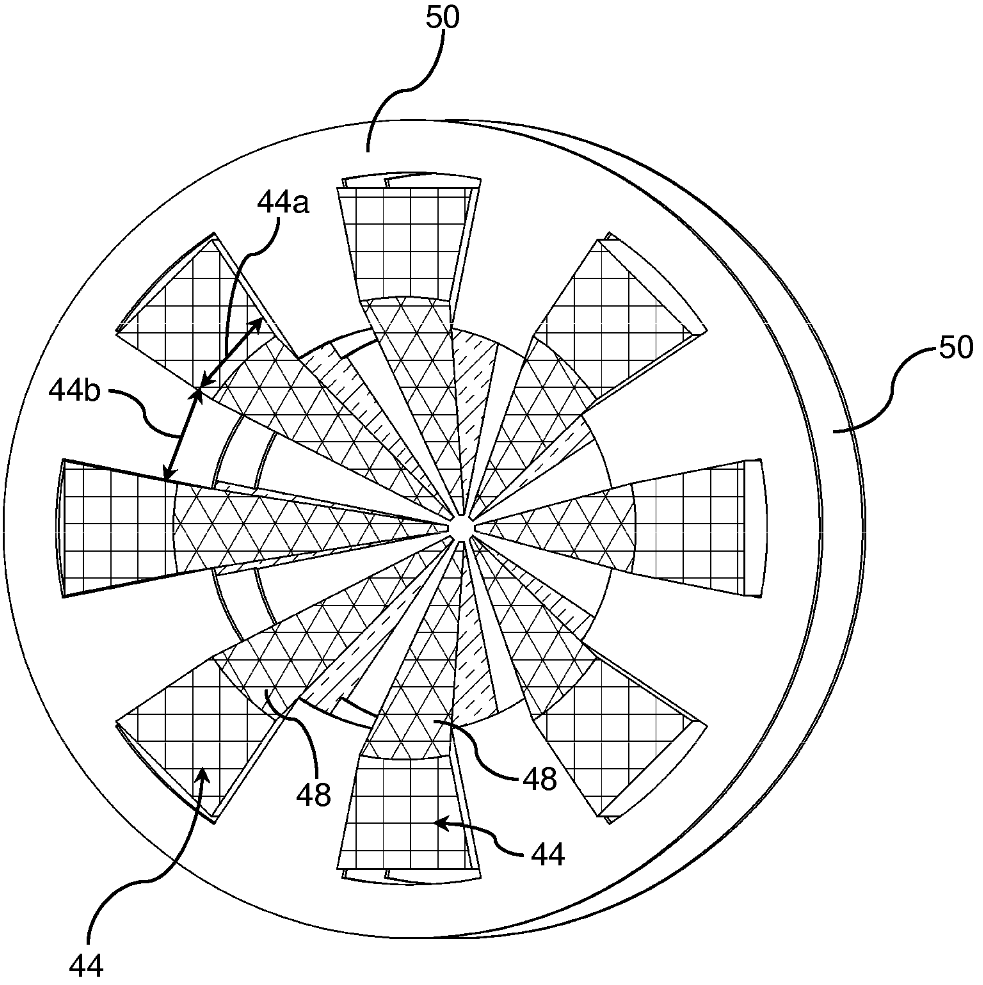

Fig. 11

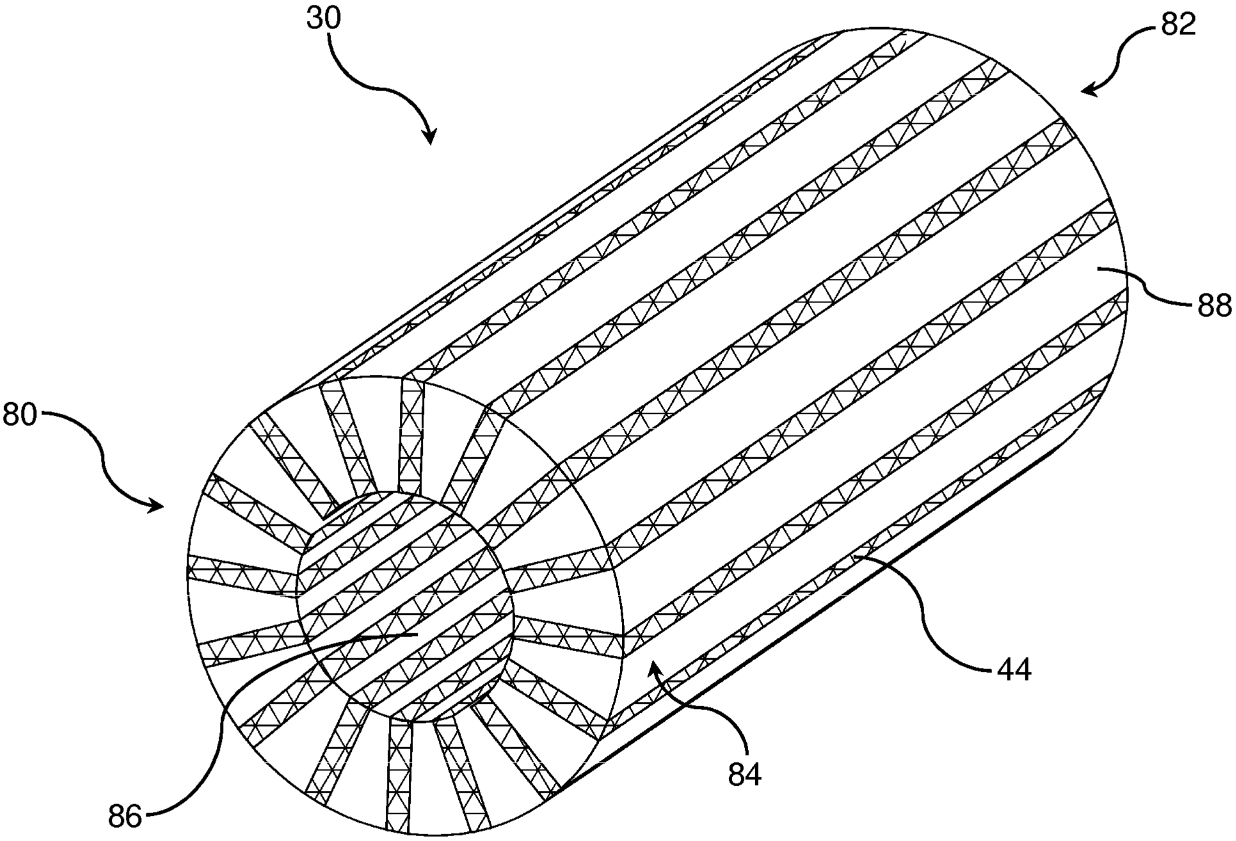

Fig. 12

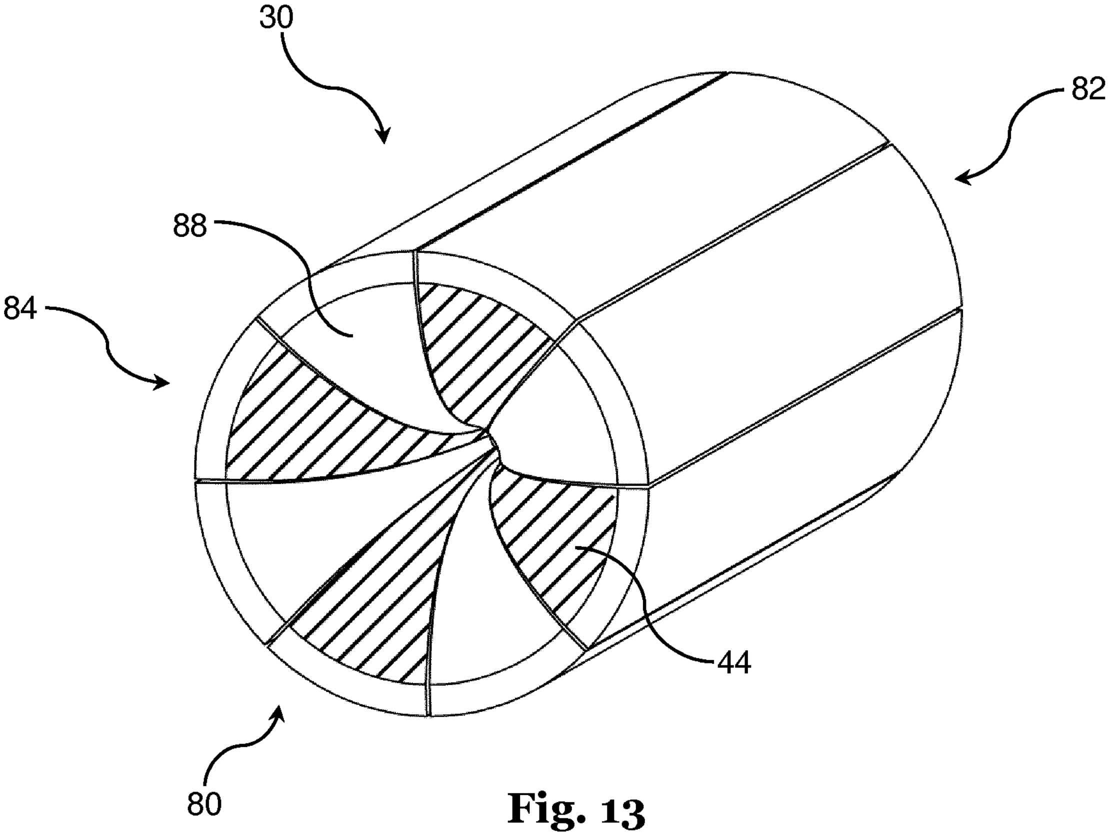

Fig. 13

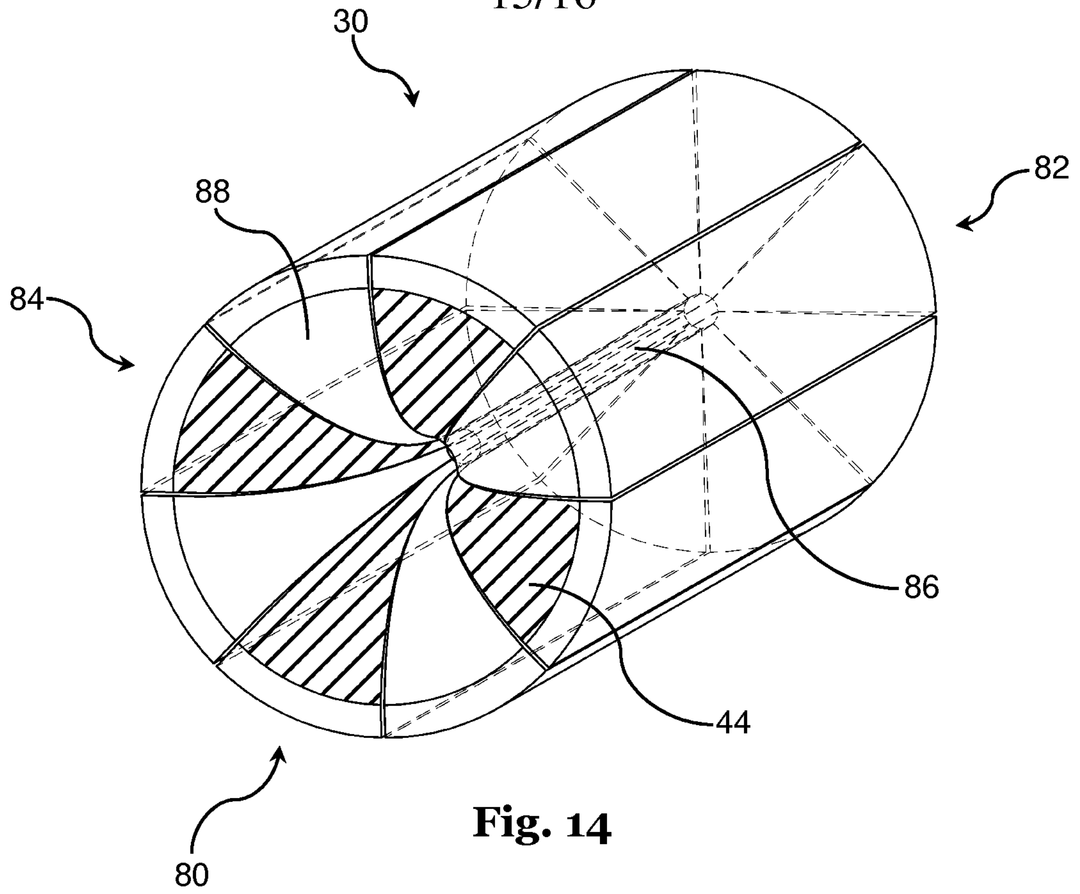

Fig. 14

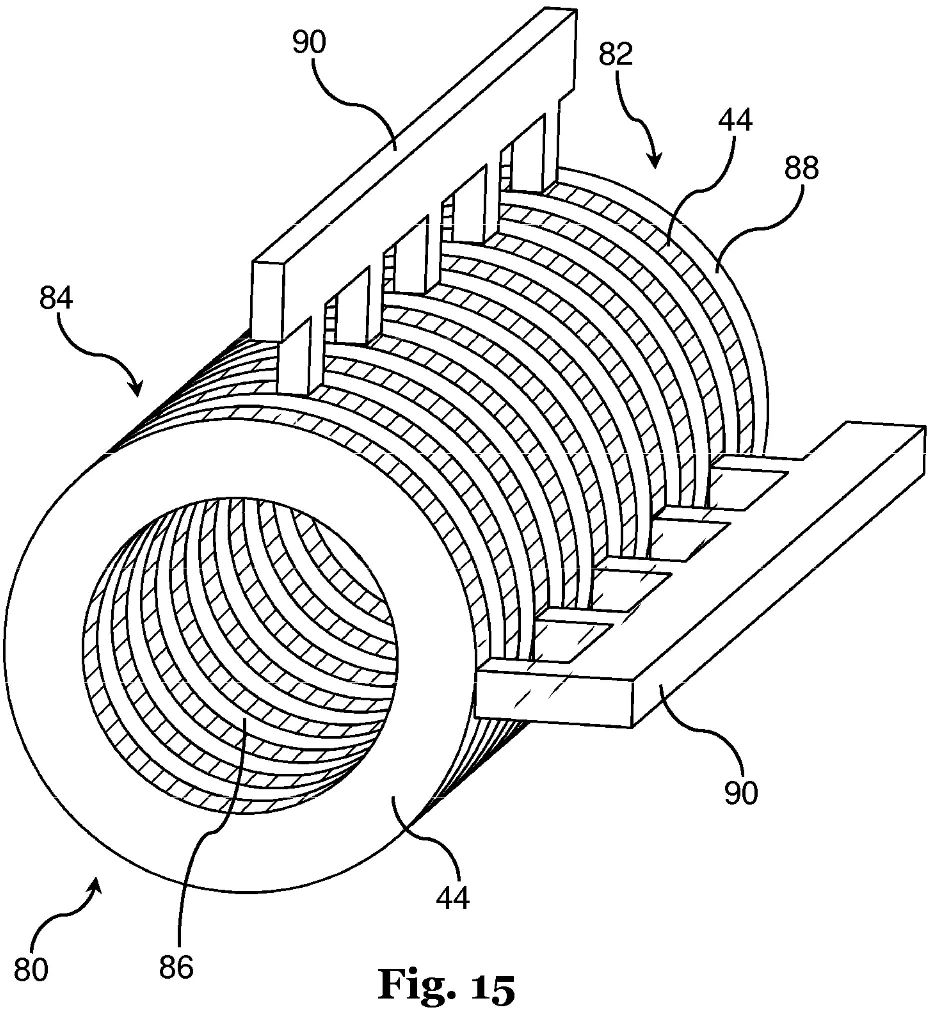

Fig. 15

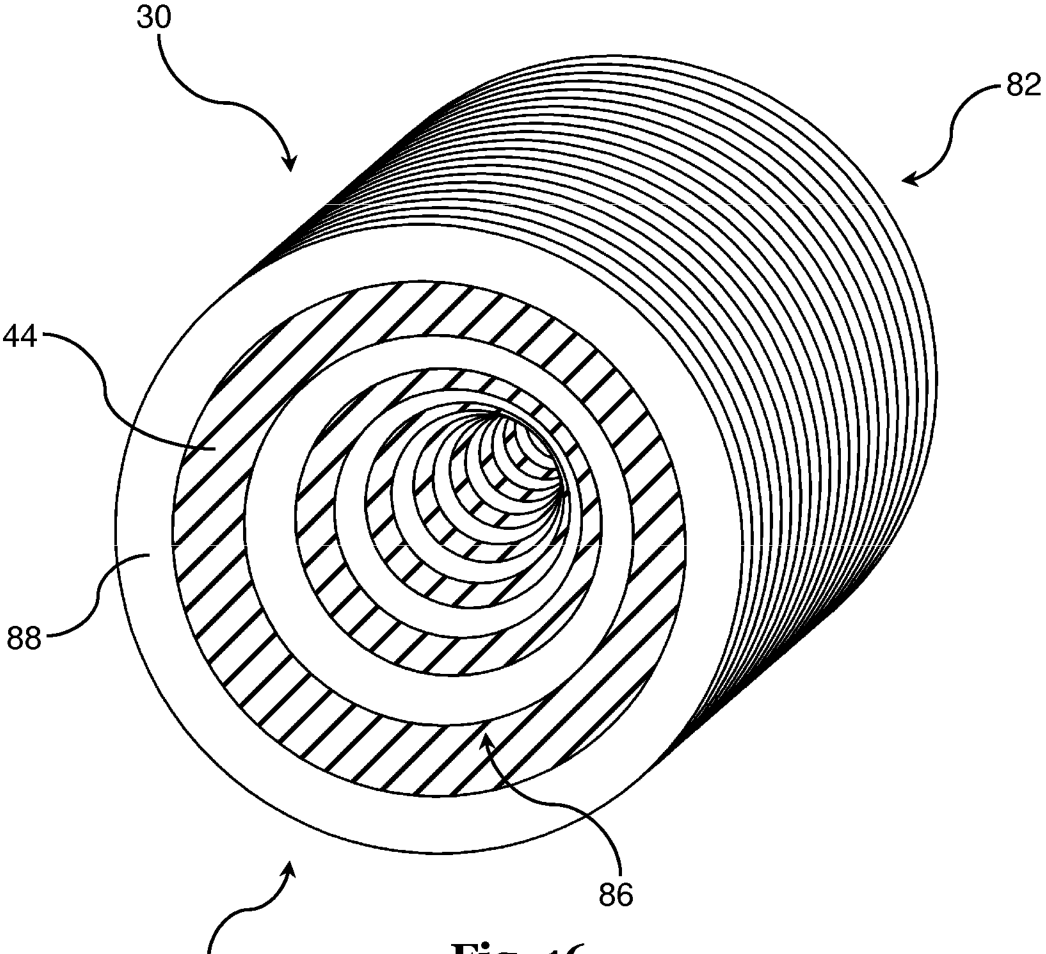

Fig. 16

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/058723

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01J49/06
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X Y	US 2003/178564 A1 (KERNAN JEFFREY T [US] ET AL) 25 September 2003 (2003-09-25) abstract; figures 16-22 paragraphs [0008], [0063] paragraphs [0083], [0084] paragraph [0013] paragraph [0147] -----	25 1-24,26
X Y	US 7 582 861 B2 (SHIMADZU CORP [JP]) 1 September 2009 (2009-09-01) abstract; figures 1-4 columns 5, 6 -----	25 1-24,26
Y	US 2010/301210 A1 (BERTSCH JAMES L [US] ET AL) 2 December 2010 (2010-12-02) abstract; figure 2A paragraphs [0049], [0051], [0052] paragraph [0041] ----- -/--	1-24,26

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search 17 June 2019	Date of mailing of the international search report 26/06/2019
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Loiseleur, Pierre

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/058723

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 6 441 370 B1 (KHOSLA MUKUL [US] ET AL) 27 August 2002 (2002-08-27) abstract; figures 5-7 column 2 -----	1-26
A	US 2014/361163 A1 (TANIGUCHI JUNICHI [JP] ET AL) 11 December 2014 (2014-12-11) paragraph [0013]; figure 12 -----	1-26

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Information on patent family members

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PCT/EP2019/058723

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