(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 4 741 656 A1

(12) # EUROPEAN PATENT APPLICATION

(43) Date of publication:
13.05.2026 Bulletin 2026/20

(21) Application number: **24212365.1**

(22) Date of filing: **12.11.2024**

(51) International Patent Classification (IPC):
F03H 1/00 *(2006.01)* ***H01J 27/22*** *(2006.01)*
H01J 37/08 *(2006.01)*

(52) Cooperative Patent Classification (CPC):
H01J 27/22; F03H 1/0012

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
GE KH MA MD TN

(71) Applicant: **ENPULSION GmbH**
1300 Wien-Flughafen (AT)

(72) Inventors:
- **KREJCI, David**
  1030 Wien (AT)
- **VASILJEVICH, Ivanhoe**
  1100 Wien (AT)
- **LITTLE, Bryan**
  1040 Wien (AT)

(74) Representative: **Weiser Voith Gugler Patentanwälte Partnerschaft**
Kopfgasse 7
1130 Wien (AT)

(54) **ION SOURCE**

(57) The present invention relates to an ion source (1), in particular an ion thruster for propelling a spacecraft, comprising a reservoir (2) for a propellant (3), a heater (4) for heating the propellant (3), an emitter (6) having one or more projections (7) for emitting ions (3') of the propellant (3), wherein the one or more projections (7) are in fluid communication with the reservoir (2), an extractor (8) facing the emitter (6) for extracting ions (3') of the propellant (3) from the emitter (6) and for accelerating the extracted ions (3') in a direction of emission (R), wherein the heater (4) comprises a projection heating unit (5) and is configured to liquefy solid propellant (3) at the one or more projections (7) by the projection heating unit (5) before the solid propellant (3) in the reservoir (2) is liquefied.

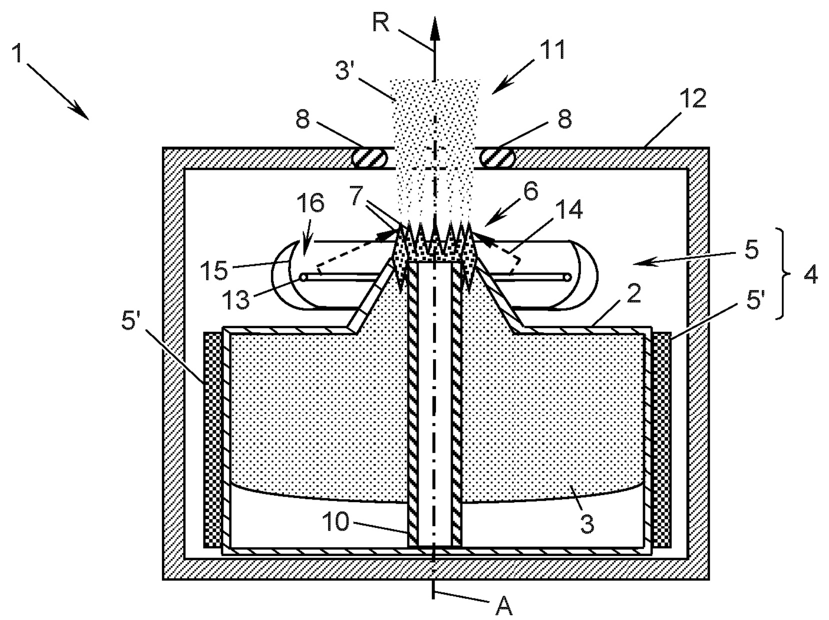

Fig. 1

EP 4 741 656 A1

Description

[0001] The present invention relates to an ion source, in particular an ion thruster for propelling a spacecraft, comprising a reservoir for a propellant that has a solid state and a liquid state and can be liquefied from the solid state into the liquid state in which the propellant has a lower density than in the solid state, a heater for heating the propellant, an emitter having one or more projections for emitting ions of the propellant when the propellant is in its liquid state, wherein the one or more projections are in fluid communication with the reservoir, and an extractor facing the emitter for extracting ions of the propellant from the emitter when the propellant is in its liquid state and for accelerating the extracted ions in a direction of emission.

[0002] Ion sources are used, e.g., for ion implantation or for creating focussed ion beams in semiconductor industry, in metal finishing, in material science and/or analysis, or in ion thrusters for the propulsion of spacecraft. In a liquid metal ion source ("LMIS"), the propellant is a metal (usually caesium, indium, mercury, etc). In so-called colloid or electrospray ion sources, the propellant is typically a molten salt or the like. In either case, the propellant is usually heated to liquefy into its liquid state in the reservoir by the heater and received therefrom by the emitter. From the emitter, ions of the liquefied propellant are electrically extracted and accelerated by the extractor to form a directed beam of ions, which in case of an ion thruster provides the thrust.

[0003] To achieve a strong electric field between the emitter and the extractor, which is necessary for ion extraction, the emitter's one or more projections are typically in the shape of cones, pyramids, triangular prisms, ridges, blades, needles or the like, that are sharp-tipped or sharp-edged to utilize the field-concentrating effect of the tip or edge. Applying the electric field to such a projection causes the formation of a so-called Taylor cone on top of the tip or edge of each of the emitter's projections, which further enhances the field-concentrating effect.

[0004] For transporting liquid propellant from the reservoir to each projection of the emitter, passive forces, like capillary effects produced by capillary ducts penetrating the emitter (as described, e.g., in AT 500 412 A1 or US 4 328 667 B) or by a porous emitter (as described, e.g., in US 2016/0297549 A1 or EP 3 724 497 A1) and/or by adhesion effects on the wetting surface of the emitter's projections (as described, e.g., in US 2009/114838 A1 or US 2011/192968 A1), are usually employed in LMIS. However, the distance over which the liquid metal can be transported by these passive forces is limited by, i.a., insufficient adhesive forces between the liquid propellant and the emitter or excessive cohesive forces within the propellant.

[0005] Under certain conditions, e.g., when the ion emission and the heating of the reservoir are paused, the propellant will solidify, i.e. freeze, and, having a higher density in its solid state compared to its liquid state, will contract in volume. Hence, upon solidification the propellant retracts from the projections of the emitter due to contraction forces in the reservoir having the larger propellant volume and cohesive forces within the propellant. In such cases of retraction of propellant, the above-mentioned passive forces might not be sufficient to restart the propellant supply to the emitter when the ion source is reheated. As a result, the ion source may degrade after having been paused. Countermeasures such as applying external forces, e.g. pressurising the reservoir from a separate pressure reservoir or by means of mechanical pumps or pistons, are often not desirable for safety, reliability and complexity reasons, particularly in spacecraft.

[0006] It is an object of the present invention to provide a safe, reliable and efficient liquid metal ion source.

[0007] This object is achieved with an ion source specified at the outset, which is distinguished in that the heater comprises a projection heating unit for feeding energy into the one or more projections, wherein the heater is configured to, when the propellant is in its solid state both in the reservoir and at the one or more projections, liquefy the propellant at the one or more projections by the projection heating unit before the propellant in the reservoir is partially of fully liquefied.

[0008] By melting the propellant at the one or more projections first, the liquefying propellant the volume of which increases due to the lower density can only expand towards the respective tops of the one or more projections and compensates for the amount of propellant that has retracted therefrom during previous solidification. An expansion towards the reservoir is blocked by the still solid propellant. After at least some of the propellant inside the reservoir is also liquefied, the above-mentioned passive forces suffice to restart the supply of liquid propellant to each projection of the emitter. Consequently, failures of the ion source due to a lack of liquid propellant at the one or more projections of the emitter can reliably be prevented. Hence, the present ion source is more reliable without requiring, e.g., pressurised reservoirs and/or mechanical pumps or pistons for forced propellant supply and is, therefore, also safer.

[0009] Favourably, the heater further comprises a reservoir heating unit for feeding energy into the reservoir to heat the propellant in the reservoir. In this case, the heater and, thus, the ion source comprises two distinct heating units, i.e., the reservoir heating unit for heating the propellant in the reservoir and the projection heating unit for heating the propellant at the one or more projections. While the reservoir heating unit may initially preheat the solid propellant in the reservoir to a temperature below its melting point, i.e., where the propellant still remains in its solid state, the projection heating unit is configured to heat the projections to a temperature above the melting point of the propellant and thereby liquefy the propellant at the one or more projections, i.e. on and/or in the projection/s. Thereafter, the reservoir heating unit can start or support liquefying the propellant in the reservoir.

[0010] In a first advantageous embodiment, the projection heating unit comprises one or more heating wires for feeding the energy into the one or more projections by irradiating them with thermal radiation. Heating wires are a particularly straightforward means of generating thermal radiation and, due to their flexible nature, can be adapted to any geometry of the emitter. Moreover, the thermal radiation fed into the one or more projections is proportional to an electrical power supplied to the heating wires. Hence, by adjusting the electrical power the rate of liquefaction and, thus, the ratio of liquefied propellant to solid propellant can easily be controlled.

[0011] In a first favourable variant of this embodiment, the projection heating unit further comprises an annular concave mirror surrounding the one or more projections, in the concavity of which the one or more heating wires are arranged for concentrating the thermal radiation onto the one or more projections. By concentrating the thermal radiation, a higher percentage thereof irradiates the one or more projections, which allows for lower heat transfer latency and higher energy efficiency of the projection heating unit. The annular mirror is particularly effective when the emitter has a single projection or is crown-shaped having an annular base from which the one or more projections protrude in axial direction.

[0012] While the shape of the annular concave mirror can be chosen from a wide variety, it is particularly favourable when the concavity of the annular concave mirror is elliptical in cross section, such that the annular concave mirror has a first and a second circular focal line, along one of which the one or more heating wires are arranged and along the other one of which the one or more projections are arranged. The annular mirror with a concavity of elliptical axial cross section, i.e., in the form of segment of an ellipse, creates a first and a second sequence of focal points along the first and the second focal line, respectively. The elliptical concavity allows for a more accurate concentration of the thermal radiation onto the one or more projections. Due to the focused concentration, higher local temperatures can be attained at the one or more projections and the rate of local liquefaction and the efficiency and controllability of the liquefaction are further increased.

[0013] In an additional or alternative second favourable variant of the first embodiment, the one or more heating wires are substantially point-shaped and the projection heating unit further comprises one or more cup-shaped mirrors, in the cup of each of which a respective one of the one or more heating wires is arranged for concentrating the thermal radiation onto a respective one of the one or more projections. Thereby, an even higher share of the thermal energy emitted by the respective heating wire is two-dimensionally concentrated onto the respective projection. This results in an even lower heat transfer latency and a further enhanced energy efficiency of the projection heating unit compared to the annular concave mirror. Moreover, individual cup-shaped mirrors can adapt to a great variety of emitter structures, e.g., wherein the emitter base is polyhedral and the one or more projections are arranged in a line or an array and are needle- or ridge-shaped or have any other shape. Thereby ensuring uniform heating in a particularly efficient way.

[0014] While the shape of the cup/s of the one or more cup-shaped mirrors can be chosen from a wide variety, it is particularly favourable when the one or more projections are needle-shaped and each one of the one or more cup-shaped mirrors is an ellipsoidal mirror and has a first and a second focal point, wherein at each first focal point a respective one of the one or more heating wires is arranged and at each second focal point a respective one of the one or more needle-shaped projections is arranged. By using ellipsoidal mirrors which concentrate most of the thermal radiation of each heating wire to a respective single point, i.e., the respective focal point, it can be precisely chosen where the thermal energy is fed into each respective projection. Hence, the rate and direction of the melting front can be predetermined specifically for each projection. This also allows for emitters of any form and projection arrangement.

[0015] In a third favourable variant of the first embodiment, the extractor additionally or alternatively has an annular groove surrounding the one or more projections, in which groove the one or more heating wires are arranged for concentrating the thermal radiation onto the one or more projections. In this variant, the thermal radiation does not only heat the one or more projections but also the extractor to a considerable extent. Some of the extracted ions (or possible weakly charged droplets of undesirably sprayed liquid propellant) may deposit on the extractor forming deposits thereon. The deposits are prone to accretion towards the emitter (known as "clogging") eventually resulting in a short-circuit between extractor and emitter leading to a complete failure of the ion source. By heating the extractor, the effects of such deposits can be mitigated by melting them and, e.g., wicking them away from the emitter.

[0016] In a modification of the aforementioned variant, the one or more heating wires are substantially point-shaped and the extractor has one or more recesses in each of which a respective one of the one or more heating wires is arranged for concentrating the thermal radiation onto the one or more projections. Thereby, the one or more heating wires can be arranged in a way corresponding to the emitter's and/or extractor's geometry to facilitate uniform heating in particular in case of non-circular projection arrangement, e.g., when the emitter base is polyhedral and the one or more projections are arranged in a line or an array.

[0017] In a further beneficial variant, the extractor itself is one of said one or more heating wires. Thereby, no separate heating wires are required, which constitutes a particularly simple and space-saving variant. Moreover, further heating wires may be applied when necessary.

[0018] In a second advantageous embodiment, the projection heating unit additionally or alternatively comprises an annular parabolic mirror for feeding the energy into the one or more projections by concentrating essentially parallel rays of incident thermal radiation onto the one or more projections. In this case the incident thermal radiation can be provided by an external source, e.g. the sun, minimising the energy consumption of the projection heating unit. This is particularly beneficial when the ion source is a thruster for a spacecraft the energy resources of which are limited.

[0019] In a modification of the second advantageous embodiment, the one or more projections are needle-shaped and the projection heating unit comprises one or more cup-shaped parabolic mirrors for feeding the energy into the one or more projections by concentrating essentially parallel rays of incident thermal radiation onto one of the one or more projections, respectively. Using individual cup-shaped parabolic mirrors for concentrating, e.g., sunlight, most of the incident thermal radiation is two-dimensionally concentrated onto the one or more needle-shaped projections such that higher local temperatures can be attained compared to the annular parabolic mirror. Moreover, individual cup-shaped parabolic mirrors can be adapted to a great variety of emitter structures, e.g., when the emitter base is polyhedral and the one or more projections are arranged in a line or an array, thereby facilitating uniform heating in a particularly efficient way.

[0020] In any of the abovementioned embodiments, the projection heating unit is advantageously offset from the emitter opposite to the direction of emission. This allows the projection heating unit to be space-savingly mounted, in particular around a bottle neck of the reservoir when it is bottle-shaped. Alternatively, the projection heating unit is beneficially offset from the emitter in the direction of emission. This increases the flexibility in designing the ion source, in particular when the reservoir is a cylinder or a cuboid. When the emitter and the projection heating unit are each rotationally-symmetric about a central axis the projection heating unit may then be axially offset along this axis opposite to or in the direction of emission.

[0021] The ion source may optionally comprise a focusing electrode which decreases divergence of the accelerated ions, thereby producing a more focused ion beam emission. Particularly in this case and when the projection heating unit is offset from the emitter in the direction of emission, it is beneficial when the focusing electrode is arranged between the projection heating unit and the one or more projections and is transmissible to the thermal radiation. Hence, both the projection heating unit and the focusing electrode can be positioned closer to the central axis and/or the projection heating unit closer to the emitter projections, thereby allowing for a particularly compact ion source design.

[0022] In a third advantageous embodiment, the projection heating unit additionally or alternatively comprises one or more laser sources, each of which is directed at a respective one of the one or more projections for feeding the energy into the one or more projections by irradiating them with laser light. Laser light is a high energy radiation beam of very small width of, e.g., a few micrometres. Hence, the laser sources, e.g. laser diodes, can be mounted rather distant from the emitter projections which increases the flexibility in designing the ion source. Moreover, the wavelength of the laser light can be specifically chosen to exploit the absorption profiles of the propellant and/or the emitter projections. Thereby, the projection heating unit can selectively heat the propellant and/or the emitter and is particularly energy efficient.

[0023] In an additional or alternative fourth advantageous embodiment, the one or more projections and/or the propellant are electrically conductive, the projection heating unit comprises an AC-current generator and, connected thereto, one or more electromagnetic coils, each of which surrounds at least one of the one or more projections for feeding the energy into the one or more projections by electromagnetic induction. Thereby, the propellant can be liquefied energy efficiently and under low latency.

[0024] In a further additional or alternative fifth advantageous embodiment, the projection heating unit comprises an AC-current generator and, connected thereto, an electromagnetic coil adjacent to the extractor to heat the extractor by electromagnetic induction, for feeding the energy into the one or more projections by irradiating them with thermal radiation from the heated extractor.

[0025] The invention shall now be described in detail on the basis of exemplary embodiments thereof with reference to the accompanying drawings, in which:

> Fig. 1 shows a first embodiment of an ion source according to the invention in a longitudinal section;
> Fig. 2 shows a variant of an emitter and a projection heating unit of the embodiment of the ion source of Fig. 1 in a top view;
> Figs. 3a, 3b, 4a, 4b, 5a, 5b, 6 and 7 show further exemplary variants and embodiments of the ion source according to the invention, each in a fragmentary longitudinal section.

[0026] Fig. 1 shows an ion source 1 which comprises a reservoir 2 for a propellant 3. The propellant 3 has a solid state and can be liquefied from its solid state into a liquid state by heating and, of course, solidifies from its liquid state into its solid state when cooling. In the liquid state, the propellant 3 has a lower density than in its solid state. In order to liquefy the propellant 3, the ion source 1 comprises a heater 4. The heater 4 comprises a projection heating unit 5 and an optional reservoir heating unit 5' which, when activated, heat and liquefy the propellant 3 as will be described in detail further down.

[0027] The ion source 1 also has an emitter 6 with one or more projections 7 for emitting ions 3' of the propellant 3 when the propellant 3 is in its liquid state. The one or more projections 7 are in fluid communication with the reservoir 2 and are thereby receiving liquefied propellant

3 from the reservoir 2 during operation of the ion source 1.

[0028] For extracting ions 3' of the propellant 3 from the emitter 6 when the propellant 3 is in its liquid state and for accelerating the extracted ions 3' in a direction of emission R, the ion source 1 comprises an extractor 8 which faces the emitter 6. A strong electric field is applied to the emitter 6 and the extractor 8 by connecting a voltage source of, e.g., a few kilovolts (kV).

[0029] In the example of Fig. 1, the emitter 6 is crown-shaped, having an annular base 9 (Fig. 3a) that is mounted on a rod 10 extending through the reservoir 2. From the annular base 9 of the emitter 6 one or more (here: seven visible needle-shaped) projections 7 protrude on that side of the emitter 6 directing away from the reservoir 2. Each projection 7 has the shape of a cone, a pyramid, a triangular prism, a ridge, a blade, (in this example) a needle, or the like and has a sharp tip or edge. In other embodiments, the emitter 6 may be directly connected to the reservoir 2 without the support of the rod 10 and/or have a different shape, e.g., without a base 9, with a base 9 that is polyhedral and/or one or more projections 7 that are arranged thereon in a line or an array etc.

[0030] Applying the strong electric field to the sharp tip or edge of each projection 7 causes the formation of a so-called Taylor cone on top of each projection 7. At the apex of the Taylor cone, the ions 3' are extracted and accelerated by the strong electric field between the extractor 8 and the emitter 6, thereby creating an ion beam 11 that is propagating in the direction of emission R away from the emitter 6 and - when the extractor 8 is mounted, e.g., in a housing 12 of the ion source 1 as in this example - away from the ion source 1.

[0031] The ion source 1 can be used, e.g., for ion implantation or for creating focused ion beams in semiconductor industry, in metal finishing, in material science and/or analysis, and particularly as an ion thruster for propelling spacecraft. Moreover, the ion source 1 may comprise or be connected to further elements, e.g. a controller, a power supply, the voltage source, a neutralizer etc., as known in the art.

[0032] The propellant 3 in the embodiment of Fig. 1 is a metal, e.g. caesium, indium, mercury, etc. In such a "liquid metal ion source" ("LMIS"), neutral atoms of the metal propellant 3, when in its liquid state, field-evaporate at the apex of the Taylor cone and negative electrons tunnel back to the surface, leaving positively charged ions 3' of the liquid metal propellant 3 for extraction. Hence, the propellant 3 is both ionised, extracted and accelerated by one and the same electric field between the extractor 8 and the emitter 6. In ion sources 1 of the "colloid" or "electrospray" type, on the other hand, the propellant 3 is, e.g., a salt which is ionized in its liquefied state such that positively or negatively charged ions are extracted from the emitter 6 and accelerated by the electric field.

[0033] For receiving the liquefied propellant 3 from the reservoir 2 at the emitter 6 and transporting it to the one or more projections 7, passive forces (here: capillary effects) are used. To this end, the emitter 6 is, e.g., penetrated by capillary ducts (not shown) or (in the present example) made of porous material. The projections 7 are likewise penetrated by capillary ducts or made of porous material and/or they have a wetting surface to which the liquefied propellant 3 adheres.

[0034] When operation of the ion source 1 is not required, heating of the reservoir 2 and emission of ions 3' may be paused. The propellant 3 then freezes, i.e. solidifies, both at the emitter 6 and in the reservoir 2. During the solidification, the propellant 3 retracts from the emitter 6 towards the reservoir 2 due to its higher density in the solid state, due to strong contraction forces inside the reservoir 2 having the larger propellant volume and due to cohesive forces within the propellant 3. However, excessive retraction of propellant 3 from the one or more projections 7 impedes a subsequent formation of a Taylor cone when restarting the ion source 1. In order to compensate for such retraction when heating the propellant 3 from its solid state upon restarting, the heater 4 is configured to liquefy the propellant 3 by the projection heating unit 5 at the one or more projections 7 before the propellant 3 in the reservoir 2 is liquefied. To this end, the projection heating unit 5 feeds energy into the one or more projections 7 to heat the propellant 3 in the one or more projections 7. When strong enough and/or when the reservoir 2 is sufficiently small, the projection heating unit 5 may be the only heating unit of the heater 4 as the liquefaction may progress from the one or more projections 7 through the whole emitter 6 into the reservoir 2, e.g., by thermal conduction.

[0035] In the example of Fig. 1, however, the heater 4 further comprises an optional reservoir heating unit 5' for feeding energy into the reservoir 2, thereby supporting the heating of the propellant 3 in the reservoir 2. The reservoir heating unit 5' in this example is a resistive heating unit abutting against the outer walls of the reservoir 2 to feed energy (here: in the form of heat) into the reservoir 2 (here: by conduction). Alternatively, the reservoir heating unit 5' may be spaced apart from and irradiate the reservoir 2 or may be a different type of heating unit, e.g., an inductive heating unit, a laser source or the like.

[0036] By additionally feeding energy into the reservoir 2 when the propellant 3 is in its solid state, the propellant 3 in the reservoir 2 is heated, e.g., to a predefined temperature which is initially below the melting point of the propellant 3. By thermal conduction also the emitter 6 with its one or more projections 7 and the propellant 3 therein or thereon are heated. However, the heater 4 will always liquefy the propellant 3 at the one or more projections 7 prior to the propellant 3 in the reservoir 2 by means of the projection heating unit 5, e.g. as exemplified below.

[0037] In the embodiment shown in Fig. 1, the projection heating unit 5 comprises one or more heating wires (here: one annular heating wire) 13, which optionally surround the emitter 6 as shown, for feeding the energy into the one or more projections 7 (here: seven visible needle-shaped projections 7). One or more heating wires 13 may additionally or alternatively be positioned between the projections 7, in particular in a central gap of the emitter 6 when it is crown-shaped or has different shape with one or more gap/s between several projections 7. When activated, the heating wires 13 generate thermal radiation 14 irradiating the projection/s 7, such that the temperature at the projection/s 7 rises. When surpassing the melting point, the propellant 3 at the one or more projections 7, i.e. the propellant 3 in and/or on the projection/s 7, is liquefied without the propellant 3 in the reservoir 2 melting yet. During liquefaction, the volume of the propellant 3 expands due to its lower density in its liquid state compared to its solid state. An expansion towards the reservoir 2 is blocked by propellant 3 that is still solid (here: both in the emitter base 9 and in the reservoir 2). Hence, the liquefied propellant 3 can only expand towards the top/s of the projection/s 7 compensating for propellant 3 previously retracted therefrom during the solidification.

[0038] With increasing energy (here: the thermal radiation 14) fed into the projection/s 7, the melting front of propellant 3 gradually moves towards the reservoir 2 and an increasing amount of the propellant 3 liquefies. This provides further expansion of liquefied propellant 3 towards the projection/s 7. After a while, when sufficient liquid propellant 3 has expanded to the projection/s 7, the propellant 3 at the rest of the emitter 6 and in the reservoir 2 is liquefied by means of the projection heating unit 5 and/or the reservoir heating unit 5'. Eventually, all of the propellant 3 is liquefied both at the emitter 6 and in the reservoir 2. When sufficient (or all) of the propellant 3 in the reservoir 2 is liquefied, the extraction and acceleration of the ions 3' may be started and the projection heating unit 5 may optionally be deactivated while the reservoir heating unit 5' keeps all the propellant 3 in its liquid state as required. This procedure of heating is performed with any type or combination of projection heating unit/s 5 described below.

[0039] The heating wires 13 can have a great variety of shapes, e.g., be long wires that meander between or surround the one or more projections 7 in a zigzag or circular (Fig. 1) shape. As shown in the example of Fig. 1, the projection heating unit 5 optionally comprises an annular concave mirror 15, e.g., a ring having a mirror 15 at its inner face, the mirror 15 being both curved in the circumferential direction of the ring surrounding the projection/s 7 and concave in the axial direction of the ring forming a concavity 16. In the concavity 16, the one or more heating wires (here: one heating wire) 13 is/are arranged. In this arrangement, the concavity 16 of the annular concave mirror 15 at least to some extent concentrates the thermal radiation 14 of the heating wire/s 13 onto the projection/s 7.

[0040] When viewed in the axial cross section illustrated in Fig. 1 the concavity 16, i.e. its line of intersection, may have a variety of shapes, e.g., be angular, polygonal (not shown) or curved (Fig. 1). Optionally, the concavity 16 of the annular concave mirror 15 is elliptical in axial cross section, i.e., a segment of an ellipse. Similar to an ellipse that has two focal points, the annular concave mirror 15 with an elliptical axial cross section has two focal lines created by respective first and second sequences of focal points. By arranging the one or more heating wires 13 along one of the focal lines and the one or more projections 7 along the other focal line, the thermal radiation 14 is concentrated onto the one or more projections 7. When the emitter 6 has only one needle-shaped projection 7, said other focal line may optionally coincide to a single point on this projection 7.

[0041] In a second variant of the first embodiment, shown in Fig. 2, the projection heating unit 5 additionally or alternatively comprises one or more, in particular two or more, separate cup-shaped, i.e. two-dimensionally concave, mirrors 17. In the cup 18, i.e. in the two-dimensional concavity, of each of the cup-shaped mirrors 17 of this embodiment, a respective one of the one or more heating wires 13 is arranged such that the thermal radiation 14 is concentrated two-dimensionally onto the one or more projections 7. To this end, the one or more heating wires 13 are substantially point-shaped. The cup-shaped mirrors 17, when more than one, may be spaced apart from each other (not shown) or, as shown in this example, joined together forming a segmented mirror (here: a ring of cup-shaped mirror segments).

[0042] The cups 18 of the one or more cup-shaped mirrors 17 may have a variety of shapes when seen in any cross section, e.g., be angular or curved. Optionally, each one of the cup-shaped mirrors 17 is an ellipsoidal mirror, i.e. a segment of an ellipsoid, such that it has a first and a second focal point. When arranging a respective one of the one or more heating wires 13 at each first focal point and a respective one of the one or more projections 7, which in this case may be needle-shaped, at each second focal point, the thermal radiation 14 of the one or more heating wires 13 is concentrated to the respective one of the one or more projections 7.

[0043] Figs. 3a and 3b show two subvariants of a third variant of the first embodiment, wherein in each of the subvariants the extractor 8 has an annular groove 19 surrounding the one or more projections 7. In the annular groove 19, the one or more heating wires (here: one heating wire) 13 is/are arranged, such that the thermal radiation 14 is to some extent concentrated onto the one or more projections 7. To this end, the annular groove 19 may have a variety of shapes, e.g., when viewed in the axial cross section illustrated in Fig. 3a and 3b, be angular (not shown), polygonal (Fig. 3a) or curved (Fig. 3b).

[0044] In a modification of the third variant, the extractor 8 has one more recesses instead of the annular groove 19 shown in Figs. 3a and 3b. In each recess, a respective one of the one or more heating wires 13 is arranged such that the thermal radiation 14 is to some extend concentrated onto the one or more projections 7. The one or more heating wires 13 are substantially point-shaped and the respective opening of each of the one or more recesses is directed towards the one more projections 7.

[0045] Within the framework of the present disclosures, "point-shaped" denotes a heating wire 13 that is short or wound such that its envelope's diameter is substantially smaller than the one or more cup-shaped mirrors 17 of the example shown in Fig. 2 or than the one or more recesses, respectively, e.g., rather in the size of the diameter of the one or more projections 7.

[0046] In a further variant which is not shown, the extractor 8 itself is one of said one or more heating wires 13, which is synonymous to one of the one or more heating wired 13 forming the extractor 8.

[0047] Figs. 4a and 4b show two modifications of a second embodiment, in each of which modifications the projection heating unit 5 comprises an annular parabolic mirror 20 which concentrates essentially parallel rays of incident thermal radiation 21 onto the one or more projections 7, thereby feeding the energy into the one or more projections 7. The source of the parallel rays of incident thermal radiation 21 may either be an internal source, e.g., a thermal radiator 22 having a wide beam of thermal radiation 21 (Fig. 4a) or an external source (Fig. 4b), in particular the sun, in which latter case the parabolic mirror 20 actually forms the projection heating unit 5. When the incident thermal radiation 21 originates from an external source either the extractor 8 or the housing 12 (here: the extractor 8) may have one or more apertures 23 allowing for a passage of the incident thermal radiation 21.

[0048] Instead of or in addition to the single annular parabolic mirror 20 shown in Fig. 4a and 4b, the projection heating unit 5 may comprise one or more separate cup-shaped parabolic mirrors (not shown), which feed the energy into the one or more projections 7 by concentrating the essentially parallel rays of incident thermal radiation 21 onto the one or more projections 7 which, in this variant, are optionally needle-shaped. The one or more cup-shaped parabolic mirrors can be either spaced apart from each other or joined together to form a ring of mirror segments.

[0049] In any of the aforementioned embodiments, the mirrors 15, 17, 20, 21 may optionally be formed by respective Fresnel reflectors.

[0050] In each of the examples shown, the projection heating unit 5 and the emitter 6 are each rotationally-symmetric about a central axis A (Fig. 1). However, the projection heating unit 5 and/or the emitter 6 may be of different shape and/or differently arranged, e.g., be linear or square when seen from the top etc. or have an irregular shape. Moreover, in each of the examples of Figs. 1, 2, 3a, 3b, 4a and 4b, the projection heating unit 5 is offset from the emitter 6 in a direction opposite to the direction of emission R, i.e., in the views of Figs. 4a and 4b below the tops of the projections 7.

[0051] In contrast, Figs. 5a and 5b show examples in which the projection heating unit 5 is offset from the emitter 6 in the direction of emission R. In this example, the projection heating unit 5 and the emitter 6 are also each rotationally symmetric about the axis A.

[0052] The ion sources 1 shown in the examples of Figs. 5a and 5b additionally comprise optional focusing electrodes 24, 25, which, in these exemplary cases, are arranged in axial direction between the projection heating unit 5 and the one or more projections 7. Focusing electrodes 24, 25 are electrodes used to decrease the divergence of the ion beam 11 as known in the art, thereby "focusing" the accelerated ions 3'. Moreover, the focusing electrodes 24, 25 may be composed in different ways.

[0053] In the variant of Fig. 5a, the focusing electrode 24 is solid and the thermal radiation 14 passes by, i.e. the projection heating unit 5 is arranged such that the trajectory of the thermal radiation 14 passes by the focusing electrode 24. In the alternative variant of Fig. 5b, on the other hand, the focusing electrode 25 is composed of an electrically chargeable wire mesh or the like that is at least largely transmissible to thermal radiation 14, such that the projection heating unit 5 can be arranged closer to the one or more projections 7 as the thermal radiation 14 passes through the focusing electrode 25, i.e., through the gaps in the wire mesh. In this variant, a longitudinal extension H of the arrangement of the focusing electrode 25 and the projection heating unit 5 can be substantially reduced compared to the variant shown in Fig. 5a.

[0054] In a third embodiment shown in Fig. 6, the projection heating unit 5 additionally or alternatively comprises one or more laser sources (here: one laser source) 26. Each one of which is directed at a respective one of the one or more projections 7 (here: one projection 7) for feeding the energy into the one or more projections 7 by irradiating them with laser light 27. Alternatively, several laser sources 26 may be directed at a single projection 7 or rather the laser light 27 of a single laser source 26 may be split by means of beam splitters and/or diffractive elements and directed at multiple projections 7.

[0055] In a fourth embodiment according to Fig. 7, the projection heating unit 5 comprises an AC current generator 28 and, connected thereto, one or more electromagnetic coils 29. Each electromagnetic coil (here: one electromagnetic coil) 29 has one or more windings and surrounds at least one of the one or more projections 7 (here: one projection 7) for feeding the energy into the one or more projections 7 by electromagnetic induction. To this end, the projection/s 7 and/or the propellant 3 are electrically conductive.

[0056] In a fifth advantageous embodiment which is not shown, the projection heating unit 5 comprises the AC-current generator and, connected thereto, an electromagnetic coil adjacent to the extractor 8 to heat the extractor 8 by electromagnetic induction. Thereby, the energy is fed into the one or more projections 7 by irradiating them with thermal radiation from the heated extractor 8.

[0057] The invention is not restricted to the specific embodiments described in detail herein, but encompasses all variants, combinations and modifications thereof that fall within the framework of the appended claims, e.g., by combining two or more of the described embodiments and variants of projection heating units 5 and their arrangements in a single ion source 1.

Claims

1. An ion source, in particular an ion thruster for propelling a spacecraft, comprising

a reservoir (2) for a propellant (3) that has a solid state and a liquid state and can be liquefied from the solid state into the liquid state in which the propellant (3) has a lower density than in the solid state,
a heater (4) for heating the propellant (3),
an emitter (6) having one or more projections (7) for emitting ions (3') of the propellant (3) when the propellant (3) is in its liquid state, wherein the one or more projections (7) are in fluid communication with the reservoir (2), and
an extractor (8) facing the emitter (6) for extracting ions (3') of the propellant (3) from the emitter (6) when the propellant (3) is in its liquid state and for accelerating the extracted ions (3') in a direction of emission (R),
characterised in that
the heater (4) comprises a projection heating unit (5) for feeding energy into the one or more projections (7) to heat the propellant (3) in the one or more projections (7), wherein the heater (4) is configured to, when the propellant (3) is in its solid state both in the reservoir (2) and at the one or more projections (7), liquefy the propellant (3) at the one or more projections (7) by the projection heating unit (5) before the propellant (3) in the reservoir (2) is liquefied.

2. The ion source according to claim 1, wherein the heater (4) further comprises a reservoir heating unit (5') for feeding energy into the reservoir (2) to heat the propellant (3) in the reservoir (2).

3. The ion source according to claim 1 or 2, wherein the projection heating unit (5) comprises one or more heating wires (13) for feeding the energy into the one or more projections (7) by irradiating them with thermal radiation (14).

4. The ion source according to claim 3, wherein the projection heating unit (5) further comprises an annular concave mirror (15) surrounding the one or more projections (7), in the concavity (16) of which the one or more heating wires (13) are arranged for concentrating the thermal radiation (14) onto the one or more projections (7).

5. The ion source according to claim 4, wherein the concavity (16) of the annular concave mirror (15) is elliptical in cross section, such that the annular concave mirror (15) has a first and a second circular focal line, along one of which the one or more heating wires (13) are arranged and along the other one of which the one or more projections (7) are arranged.

6. The ion source according to any one of claims 3 to 5, wherein the one or more heating wires (13) are substantially point-shaped and the projection heating unit (5) further comprises one or more cup-shaped mirrors (17), in the cup (18) of each of which a respective one of the one or more heating wires (13) is arranged for concentrating the thermal radiation (14) onto a respective one of the one or more projections (7).

7. The ion source according to claim 6, wherein the one or more projections (7) are needle-shaped and each of the one or more cup-shaped mirrors (17) is an ellipsoidal mirror and has a first and a second focal point, wherein at each first focal point a respective one of the one or more heating wires (13) is arranged and at each second focal point a respective one of the one or more needle-shaped projections (7) is arranged.

8. The ion source according to any one of claims 3 to 7, wherein the extractor (8) is one of said one or more heating wires (13).

9. The ion source according to any one of claims 3 to 8, wherein the extractor (8) has an annular groove (19) surrounding the one or more projections (7), in which groove (19) the one or more heating wires (13) are arranged for concentrating the thermal radiation (14) onto the one or more projections (7) .

10. The ion source according to any one of claims 3 to 8, wherein the one or more heating wires (13) are substantially point-shaped and the extractor (8) has one or more recesses in each of which a respective one of the one or more heating wires (13) is arranged for concentrating the thermal radiation (14) onto the one or more projections (7).

11. The ion source according to any one of claims 1 to 10, wherein the projection heating unit (5) comprises an annular parabolic mirror (20) for feeding the energy into the one or more projections (7) by concentrating essentially parallel rays of incident thermal radiation (21) onto the one or more projections (7).

12. The ion source according to any one of claims 1 to 10, wherein the one or more projections (7) are needle-shaped and the projection heating unit (5) comprises one or more cup-shaped parabolic mirrors for feeding the energy into the one or more projections (7) by concentrating essentially parallel rays of incident thermal radiation (21) onto one of the one or more projections (7), respectively.

13. The ion source according to any one of claims 3 to 12, wherein the projection heating unit (5) is offset from the emitter (6) opposite to the direction of emission (R).

14. The ion source according to any one of claims 3 to 12, wherein the projection heating unit (5) is offset from the emitter (6) in the direction of emission (R).

15. The ion source according to claim 14, wherein the ion source (1) further comprises a focusing electrode (24, 25) for focusing the accelerated ions (3'), which focusing electrode (24, 25) is arranged between the projection heating unit (5) and the one or more projections (7) and is transmissible to the thermal radiation (14).

16. The ion source according to any one of claims 1 to 15, wherein the projection heating unit (5) comprises one or more laser sources (26), each of which is directed at a respective one of the one or more projections (7) for feeding the energy into the one or more projections (7) by irradiating them with laser light (27).

17. The ion source according to any one of claims 1 to 16, wherein the one or more projections (7) and/or the propellant (3) are electrically conductive and the projection heating unit (5) comprises an AC-current generator (28) and, connected thereto, one or more electromagnetic coils (29), each of which surrounds at least one of the one or more projections (7) for feeding the energy into the one or more projections (7) by electromagnetic induction.

18. The ion source according to any one of claims 1 to 17, wherein the projection heating unit (5) comprises an AC-current generator and, connected thereto, an electromagnetic coil adjacent to the extractor (8) to heat the extractor (8) by electromagnetic induction, for feeding the energy into the one or more projections (7) by irradiating them with thermal radiation (14) from the heated extractor (8).

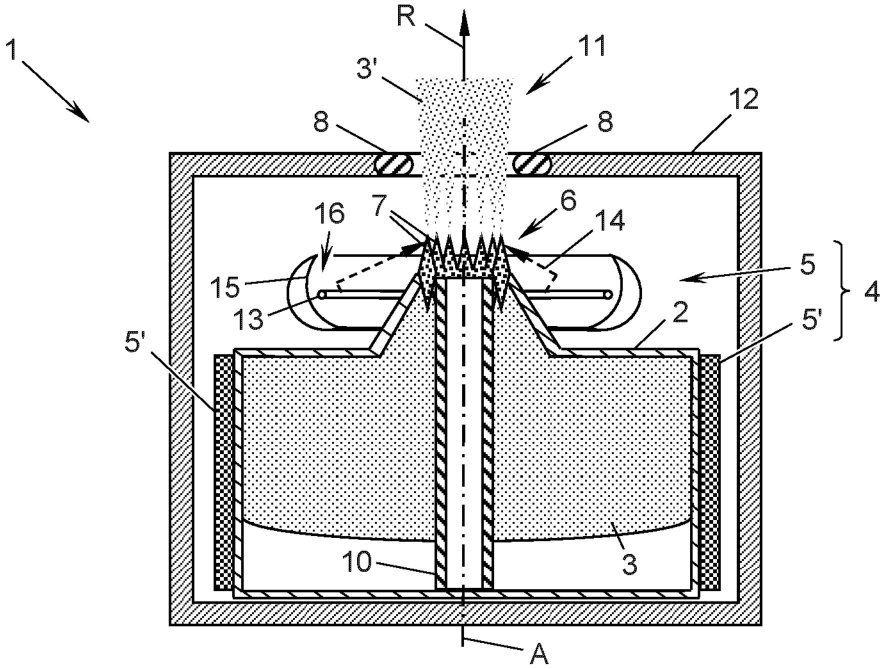

Fig. 1

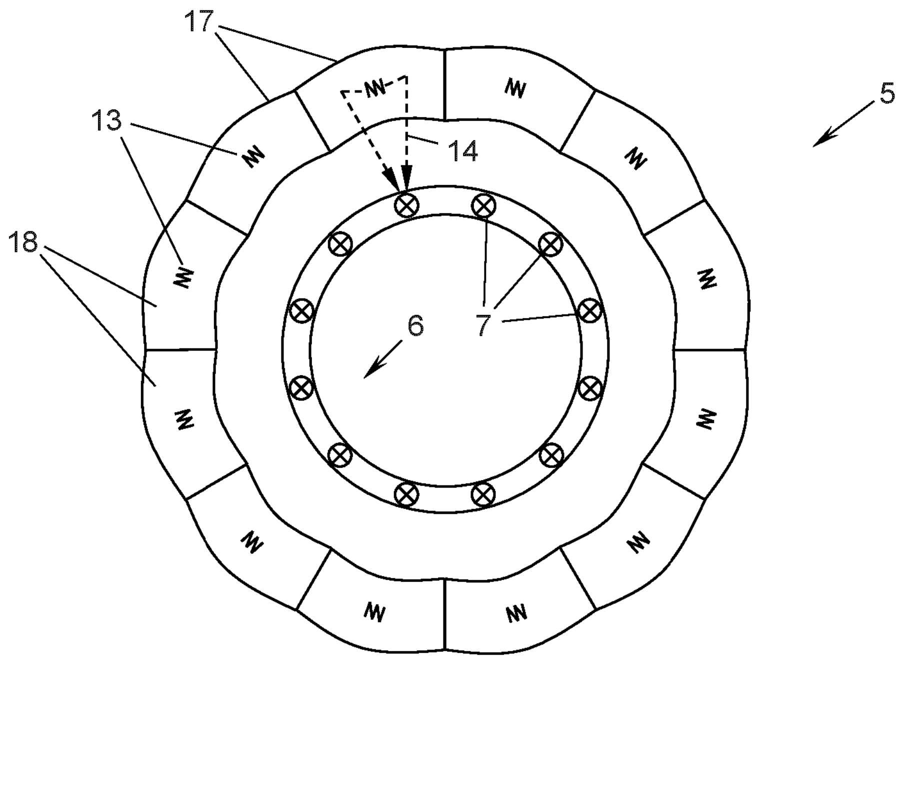

Fig. 2

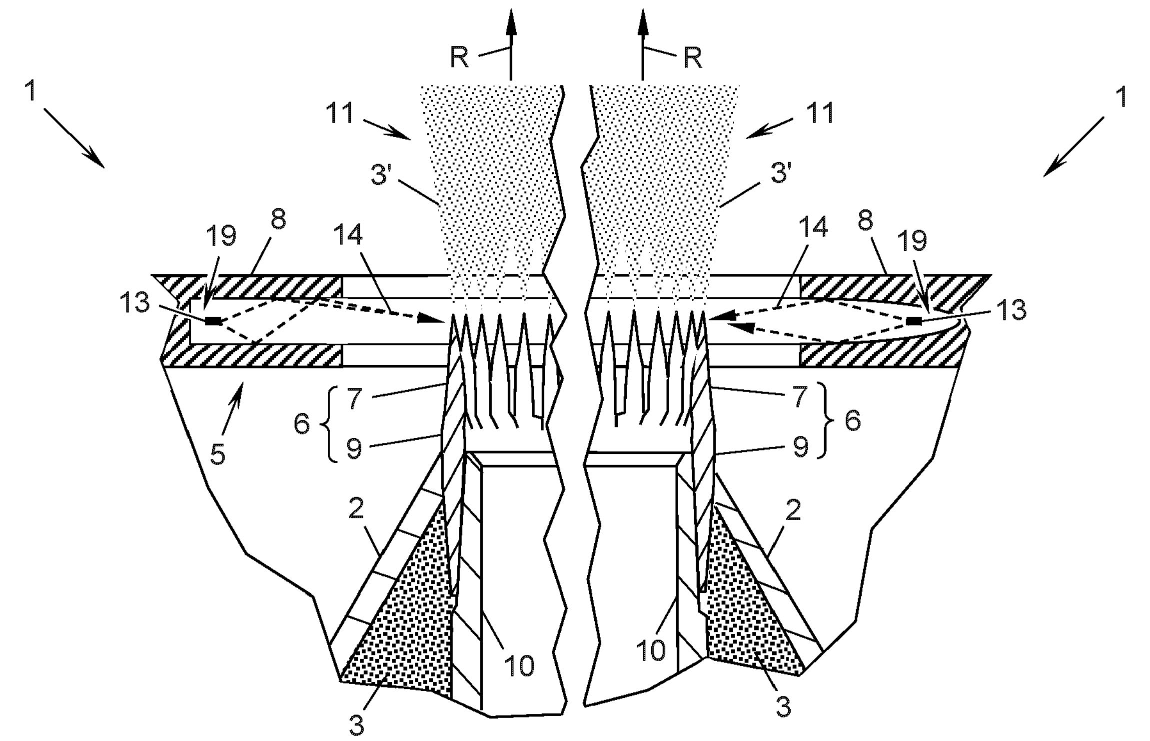

Fig. 3a Fig. 3b

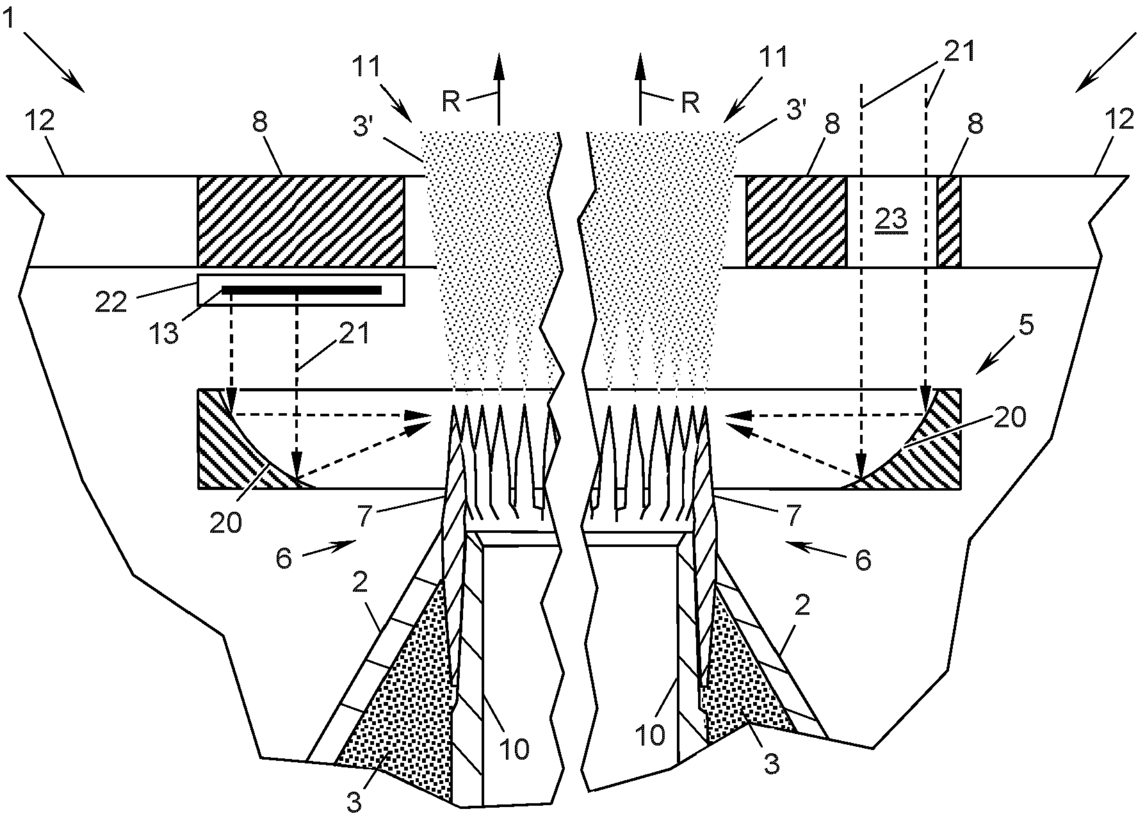

Fig. 4a Fig. 4b

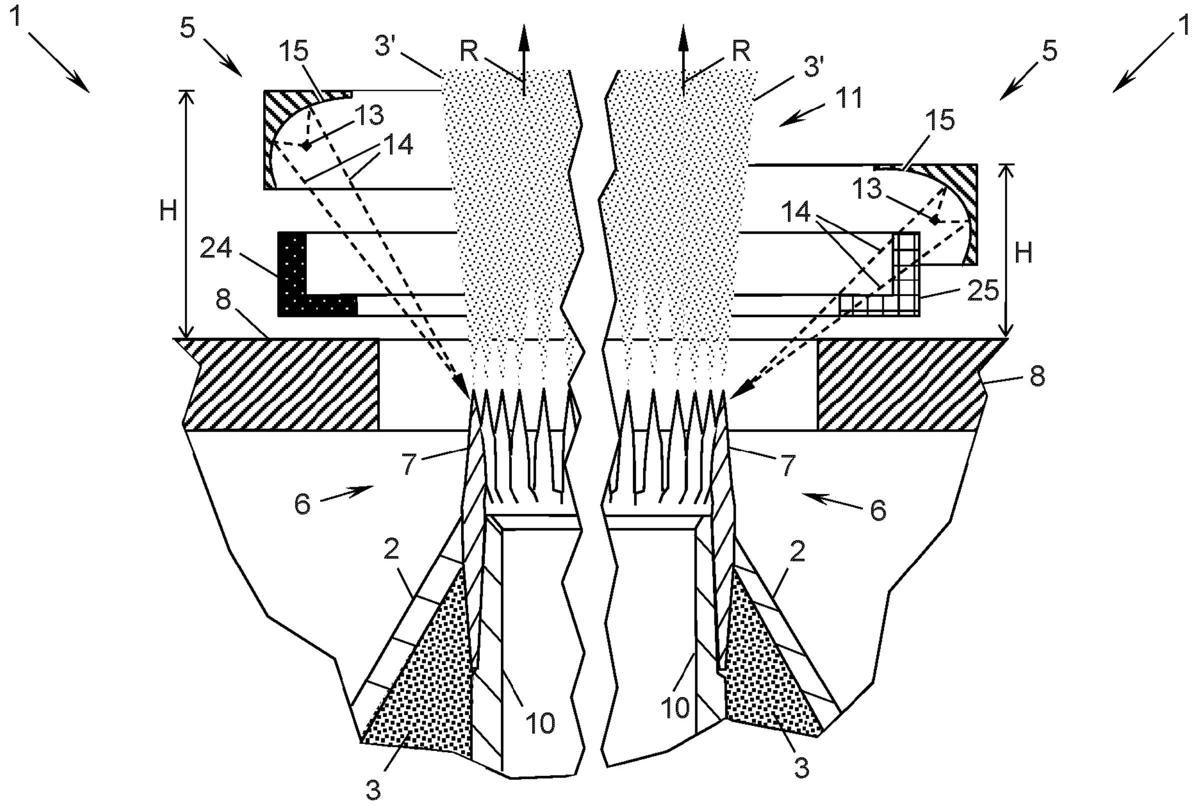

Fig. 5a *Fig. 5b*

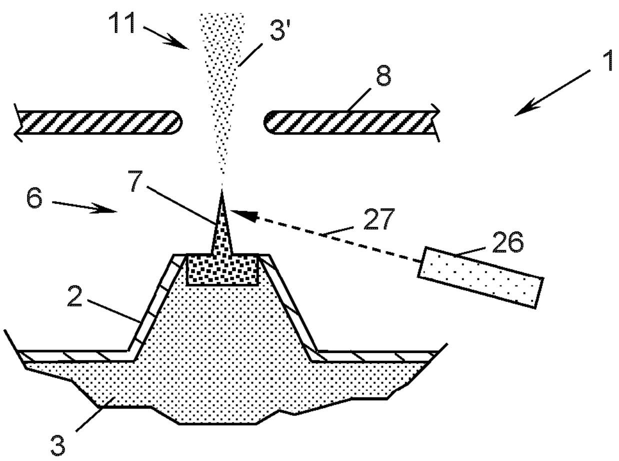

Fig. 6

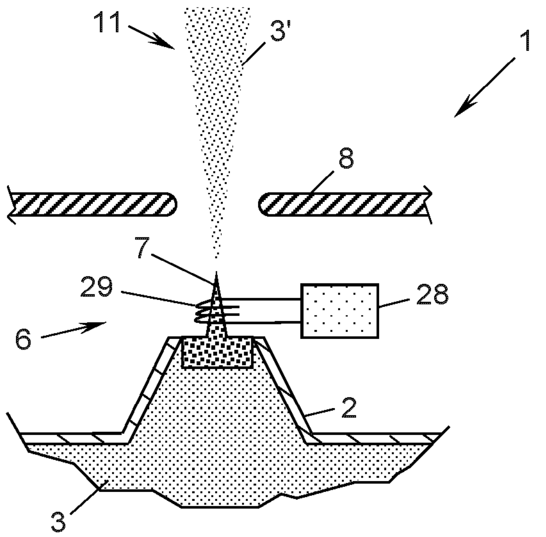

Fig. 7

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 24 21 2365

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X Y	JP S60 63855 A (HITACHI LTD) 12 April 1985 (1985-04-12) * abstract; figures 1, 4 *	1-15 16-18	INV. F03H1/00 H01J27/22
Y	RU 2 738 136 C1 (BOLOTIN NIKOLAJ BORISOVICH [RU]) 8 December 2020 (2020-12-08) * abstract; figure 1 *	16	ADD. H01J37/08
Y	JP S59 31541 A (HITACHI LTD) 20 February 1984 (1984-02-20) * abstract; figure 2 *	17,18	
A	US 2023/369003 A1 (VASILJEVICH IVANHOE [AT]) 16 November 2023 (2023-11-16) * the whole document *	1-18	
A	US 2022/205437 A1 (GIERAK JACQUES [FR]) 30 June 2022 (2022-06-30) * the whole document *	1-18	TECHNICAL FIELDS SEARCHED (IPC)
A	JP S60 163356 A (HITACHI LTD) 26 August 1985 (1985-08-26) * abstract; figures 1-4 *	1-18	F03H H01J

The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
The Hague	1 May 2025	Loiseleur, Pierre

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
....
& : member of the same patent family, corresponding document

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO.

EP 24 21 2365

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

01-05-2025

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
JP S6063855	A	12-04-1985	NONE			
RU 2738136	C1	08-12-2020	NONE			
JP S5931541	A	20-02-1984	NONE			
US 2023369003	A1	16-11-2023	EP	4276307	A1	15-11-2023
			US	2023369003	A1	16-11-2023
US 2022205437	A1	30-06-2022	CN	113574274	A	29-10-2021
			EP	3942180	A1	26-01-2022
			FR	3094046	A1	25-09-2020
			US	2022205437	A1	30-06-2022
			WO	2020187835	A1	24-09-2020
JP S60163356	A	26-08-1985	NONE			

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- AT 500412 A1 **[0004]**
- US 4328667 B **[0004]**
- US 20160297549 A1 **[0004]**
- EP 3724497 A1 **[0004]**
- US 2009114838 A1 **[0004]**
- US 2011192968 A1 **[0004]**