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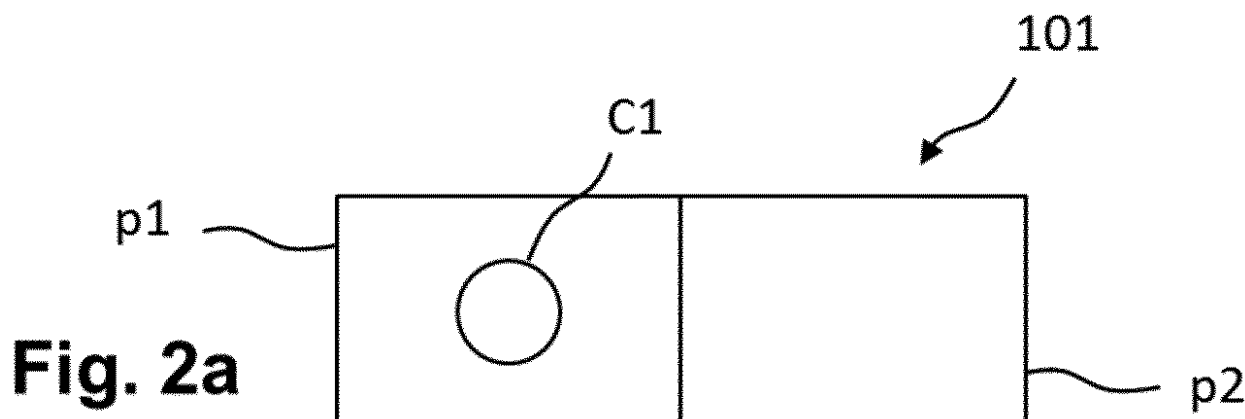
(71) Applicants:  
• **L'UNIVERSITE D'AIX-MARSEILLE**  
**13284 Marseille Cedex 07 (FR)**  
• **CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE -CNRS-**  
**75794 Paris Cedex 16 (FR)**  
• **Centre National d'Etudes Spatiales**  
**75039 Paris Cedex 01 (FR)**

(72) Inventors:  
• **Knoop, Martina**  
**13005 Marseille (FR)**  
• **Champenois, Caroline Antoinette Madeleine**  
**13190 Allauch (FR)**  
• **Houssin, Marie**  
**13012 Marseille (FR)**  
• **Kamsap, Marius Romuald**  
**13014 Marseille (FR)**  
• **Pedregosa Gutierrez, Jofre**  
**13012 Marseille (FR)**

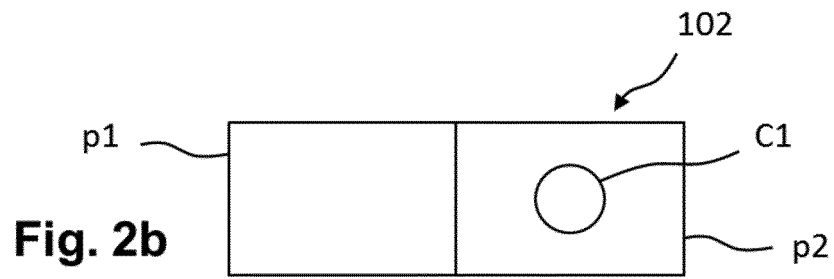
(74) Representative: **Cabinet Camus Lebkiri**  
**25, Rue de Maubeuge**  
**75009 Paris (FR)**

(54) **Method of accumulating ions**

(57) According to an aspect of the invention, there is provided a method of accumulating ions in an ion trap having a first part (p1) and a second part (p2), the first and second parts being separated by a central electrode, said method comprising a step (102) of transferring a first ion cloud (C1) from the first part to the second part by applying a potential variation on the central electrode during a duration that is less than 1 ms, the first ion cloud being trapped in the first part before said step of transfer and the first ion cloud being trapped in the second part after said step of transfer.



**Fig. 2a**



## Description

### FIELD

[0001] The present invention relates to a method of transferring, or transporting, ions between a first part and a second part of an ion trap, or between a first ion trap and a second ion trap. The present invention also relates to a method of accumulating ions in an ion trap. In the present document, the term "accumulation of ions in an ion trap" means "addition of ions to an already existing ion cloud confined in an ion trap".

### BACKGROUND

[0002] Transporting charged particles between different traps has become an important feature in high-precision spectroscopy experiments of different types. In many experiments in atomic and molecular physics, to obtain the best conditions, the optical probing of the ions is not carried out at the same location as the creation or state preparation.

[0003] Due to their extremely long storage times and their unique features, radiofrequency (RF) traps are a popular tool for many high-resolution experiments, from quantum information to cold chemistry. They allow the individual manipulation and interrogation of ion ensembles from a few units to a million particles, with the possibility to optimize trapping geometries and cloud sizes. Ions are stored in these ion traps by application of a radiofrequency (RF) voltage and an optional DC voltage. Transporting ions has always been an important ingredient in chemistry or mass spectrometry, where ions are created in external sources, and have to be brought to and accumulated in a trap. This issue is even more important if the created ions are rare or difficult to produce. In this case, the accumulation of ions in the trap is another key element for the optimisation of the signal-to-noise ratio. The transfer of ions is central in frequency-metrology experiments, in order to use two separated trapping zones for state-preparation and probing of the ions. Shuttling also gains in importance in quantum information where scalable architectures require the possibility to move ions from one site to another.

[0004] Different groups have addressed the question of transport of single ions in microtraps, mainly for quantum computation applications, as it is a crucial issue for scalable architectures of ion traps. In these experiments, a major issue during transport is the heating of the transferred atoms or molecules, and as a consequence the large majority of applied protocols uses a cooling mechanism and/or a tailored protocol to limit heating and therefore reduce perturbation and loss of the sample. The implementation of robust gate operations also requires very high transfer efficiencies. In micro-traps, the transport distances for a single ion are of the order of a few 100  $\mu\text{m}$ . The objective is to keep the ions in the vibrational ground state. Care is taken to translate the ions in a quasi-

constant potential well, which requires a large number of electrodes to design the trapping potential at every step. Speed is an additional issue which has to be taken into account, as shuffling ions between different sites is only a preparatory or intermediate task and should not last longer than the computational gate.

[0005] An atomic ion clock with two ion traps and a method to transfer ions between said two ion traps is described in patent US 2009/0058545 A1. This document describes ion shuttling between a first ion trap and a second ion trap, allowing separation of the state selection process from the clock microwave resonance process so that each trap may be independently optimized for its task. This document explains that a DC voltage ramp is applied to control the ion shuttling between a quadrupole ion trap and a more weakly confining multipole ion trap, that the voltage ramping used to move ions from one trap to the other should proceed slowly to allow for ion thermalization with a buffer gas, and that a ramp voltage change of state that is more than 100 ms and as much as 500 ms is typically required.

[0006] In this context, there is a need for a method and device allowing to transport or transfer an ion cloud confined in a first ion trap toward a second ion trap, or to transport or transfer an ion cloud confined in a first part of an ion trap toward a second part of said ion trap; said transport or transfer being faster than that of the existing state of art.

[0007] There is also a need for a method and device allowing to transport or transfer an ion cloud between a first part of an ion trap and a second part of said ion trap, or between a first ion trap and a second ion trap, said transport being faster than that of the existing state of the art without needing any cooling of said ion cloud.

[0008] There is also a need for a method and device allowing to add ions to an already existing ion cloud confined in an ion trap.

### SUMMARY

[0009] The present invention addresses the technical problems identified above. An objective of the invention is to provide a method of accumulating ions in an ion trap having a first part and a second part, the first and second parts being separated by a central electrode and the first and second parts being asymmetrical, said method comprising a step of transferring a first ion cloud from the first part to the second part by applying a potential variation on the central electrode during a duration that is less than 1 ms, the first ion cloud being trapped in the first part before said step of transfer and the first ion cloud being trapped in the second part after said step of transfer.

[0010] The expression "the first and second parts being asymmetrical" means that the first and second parts may be asymmetrical in potential, or in geometry, or both. The expression "the first and second parts being asymmetrical in potential" means for example that the first and second parts have different DC potentials.

**[0011]** The invention allows the transfer or transport of an ion cloud between a first part of an ion trap and a second part of said ion trap, or between a first ion trap and a second ion trap, in a duration that is less than 1 ms. That is, the invention allows a transfer or transport that is about at least 100 times faster than the previous state of art.

**[0012]** Apart from the characteristics mentioned above in the previous paragraph, the method of accumulation according to an aspect of the invention may have one or several complementary characteristics among the following characteristics considered individually or in any technically possible combinations:

- The method further comprises a step of transferring back the first ion cloud from the second part to the first part by applying a potential variation on the central electrode during a duration that is less than 1 ms, the first ion cloud being trapped in the second part before said step of transfer and the first ion cloud being trapped in the first part after said step of transfer.
- The method further comprises:
  - o a step of introducing a second ion cloud in the first part of the ion trap, and
  - o a step of transferring the second ion cloud from the first part to the second part by applying a potential variation on the central electrode during a duration that is less than 1 ms, the second ion cloud being trapped in the first part before said step of transfer and the second ion cloud being trapped with the first ion cloud in the second part after said step of transfer.

**[0013]** Said method advantageously allows the accumulation of ions in the second part of the ion trap, that is to say, the addition of ions of the second cloud to the already existing first ion cloud confined in the second part of the ion trap. Said method also advantageously allows the sequential creation of a multi-species ion cloud, in the case where the ions of the first ion cloud are of a first species, and the ions of the second ion cloud are of a second species that is different from the first species.

- The method further comprises a step of transferring the first ion cloud and the second ion cloud from the second part to the first part by applying a potential variation on the central electrode during a duration that is less than 1 ms, the first and second ion clouds being trapped in the second part before said step of transfer, and the first and second clouds being trapped in the first part after said step of transfer.
- The method further comprises a step of transferring the first ion cloud and the second ion cloud from the first part back to the second part by applying a po-

tential variation on the central electrode during a duration that is less than 1 ms, the first and second ion clouds being trapped in the first part before said step of transfer, and the first and second ion clouds being trapped in the second part after said step (105') of transfer.

- The method of accumulating ions according to an aspect of the invention, wherein a static potential asymmetry is created between the first part and the second part by introducing a static potential difference between the first part and the second part.
- The method of accumulating ions according to an aspect of the invention, wherein a geometrical asymmetry is created between the first part and the second part by choosing a first geometry for the first part and a second geometry that is different from the first geometry for the second part.

**[0014]** Another aspect of the invention provides a device comprising:

- an ion trap having a first part and a second part, the first and second parts being separated by a central electrode and the first and second parts being asymmetrical, and
- means for applying a potential variation on the central electrode to transfer a first ion cloud from the first part to the second part by applying a potential variation on the central electrode during a duration that is less than 1 ms, the first ion cloud being trapped in the first part before said transfer and the first ion cloud being trapped in the second part after said transfer.

**[0015]** Apart from the characteristics mentioned in the previous paragraph, the device according to an aspect of the invention may have one or several complementary characteristics among the following characteristics considered individually or in any technically possible combinations:

- The first part has a first static potential and the second part has a second static potential that is different from the first static potential, the first and second parts being asymmetrical with a static potential asymmetry.
- The first part has a first geometry and the second part has a second geometry that is different from the first geometry, the first and second parts being asymmetrical with a geometrical asymmetry.

**[0016]** Other features and advantages of the invention will become apparent on examining the detailed specifications hereafter and the appended drawings.

## BRIEF DESCRIPTION OF THE FIGURES

### [0017]

- Figure 1a schematically illustrates a double ion trap having a first ion trap and a second ion trap.
- Figure 1b schematically illustrates an ion trap separated into a first part and a second part.
- Figure 2a schematically illustrates a step of introducing a first ion cloud in the first ion trap, according to an aspect of the invention.
- Figure 2b schematically illustrates a step of transferring the first ion cloud from the first ion trap to the second ion trap, according to an aspect of the invention.
- Figure 2c schematically illustrates a step of introducing a second ion cloud in the first ion trap, while the first ion cloud remains in the second ion trap, according to an aspect of the invention.
- Figure 2d schematically illustrates a step of transferring the second ion cloud from the first ion trap to the second ion trap in order to trap both the first and second ion clouds in the second ion trap, according to an aspect of the invention.
- Figure 3 schematically illustrates a diagram of the steps of a method of accumulating ions according to an aspect of the invention.
- Figure 4 illustrates the fraction of residual ions in the first ion trap and in the second ion trap, as a function of the duration of a gate function applied to a central electrode separating the first ion trap and the second ion trap, according to an aspect of the invention.
- Figure 5 illustrates the number of ions in the second ion trap as a function of the number of transport cycles, according to an aspect of the invention.
- Figure 6 illustrates the cumulated ion number in the second ion trap as a function of the transfer cycle, without any cooling process, according to an aspect of the invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0018] Some embodiments of apparatus and methods in accordance with embodiments of the present invention are now described, by way of example only, and with reference to the accompanying drawings. The description is to be regarded as illustrative in nature and not as restricted.

[0019] The terms "transfer" and "transport" are indifferently used in the present description.

[0020] Figure 1a schematically illustrates a double ion trap 1 comprising:

- a first ion trap P1 having a first end and a second end;
- a second ion trap, P2 having a first end and a second end;
- a first DC electrode E1 closing the first ion trap P1

at its first end; a second DC electrode E2 closing the first ion trap P1 at its second end; a third DC electrode E3 closing the second ion trap P2 at its first end, and a fourth DC electrode E4 closing the second ion trap P2 at its second end.

[0021] The first ion trap P1 may typically be a radiofrequency (RF) trap, and in particular a RF multipole trap. The second ion trap P2 may typically be a RF trap, and in particular a RF multipole trap. In the present description, the term "multipole trap" means a trap comprised of more than one electrode. A quadrupole trap is a particular embodiment of a multipole trap.

[0022] Figure 1a also shows:

- a light source S, for example a Hg lamp; and
- a photomultiplier PM.

[0023] The first ion trap P1 and the second ion trap P2 are aligned along a common axis. Said first ion trap P1 and second ion trap P2 may be linear RF traps, or 3D RF traps. In the case where said first ion trap P1 and second ion trap P2 are RF multipole traps, they may be of the same pole order, or alternatively of different pole orders. Said first ion trap P1 and second ion trap P2 may in particular be quadrupole RF traps. In a particular embodiment, the first ion trap P1 and the second ion trap P2 may be two linear quadrupole RF traps of radius  $r_0 = 3.9$  mm and length  $l = 21$  mm, aligned along a common Z-axis - the length  $l$  being measured along said Z-axis.

[0024] Figure 1b illustrates an ion trap 2 separated into a first part p1 and a second part p2, the ion trap 2 having a first end and second end, a first DC electrode e1 closing the ion trap 2 at its first end, a second DC electrode e2 closing the ion trap at 2 its second end, a central DC electrode Ec separating the first part p1 from the second part p2.

[0025] Said ion trap 2 may be a linear RF trap, or a 3D RF trap. The ion trap 2 may be a multipole RF trap and in particular a quadrupole RF trap. In a particular embodiment, the multipole RF trap 2 is a linear quadrupole RF trap of radius  $r_0 = 3.9$  mm, aligned along the Z-axis, the first part p1 and the second part p2 being each of length  $l = 21$  mm, said length  $l$  being measured along the Z-axis.

[0026] The double trap 1, illustrated in figure 1a, that comprises two ion traps P1 and P2, and the ion trap 2, illustrated in figure 1b, that comprises a first part p1 and a second part p2, may both be used to perform a method of accumulation according to an aspect of the present invention.

[0027] Figures 2a, 2b, 2c and 2d schematically illustrate steps of a method 100 of accumulating ions according to an aspect of the invention. The double ion trap 1 or the ion trap 2 previously described may typically be used to perform said method 100. The following description is made for the case where the ion trap 2 is used, but is also valid for the case where the double ion trap 1 is used. As a consequence, in the following description,

the terms "first part p1 of the ion trap 2" and "first ion trap P1 of the double ion trap 1" are indifferently employed. The terms "second part p2 of the ion trap 2" and "second ion trap P2 of the double ion trap 1" are indifferently employed. The terms "central DC electrode Ec" and "second DC electrode E2 and third DC electrode E3" are indifferently employed.

**[0028]** Figure 2a schematically illustrates a step 101 of introducing or creating a first ion cloud C1 in the first part p1 of the ion trap 2.

**[0029]** Figure 2b schematically illustrates a step 102 of transferring the first ion cloud C1 from the first part p1 to the second part p2 of the ion trap 2, by applying a potential variation on the central DC electrode Ec during a duration that is less than 1 ms. Such a transfer time less than 1 ms is to be compared with the longer transfer times, of about 100 ms to 500 ms, typically observed in the state of the art. The applied potential variation is also called "transport function". Studies have shown that the analytic form of said transport function is a key issue in transport.

**[0030]** An optional step 102', illustrated on figure 3, of transferring the first ion cloud C1 from the second part p2 back to the first part p1 may then be performed, by applying a potential variation on the central DC electrode Ec during a duration that is less than 1 ms. The first ion cloud C1 may thus be quickly transferred back and forth between the first part p1 and the second part p2, each transfer step during less than 1 ms. These transfer times are to be compared with the longer transfer times, of about 100 ms to 500 ms, that are typically observed in the state of the art. The potential variation applied during the step 102 of transferring the first ion cloud C1 from the first part p1 to the second part p2, and the potential variation applied during the optional step 102' of transferring the first ion cloud C1 from the second part p2 back to the first part p1, may be identical or alternatively different in their amplitude and/or in their temporal evolution.

**[0031]** Figure 2c schematically illustrates an optional step 103 of introducing a second ion cloud C2 in the first part p1 of the ion trap 2, the first ion cloud C1 being and remaining in the second part p2 of the ion trap 2. The method comprising the step 102 and the optional step 103 allows the accumulation of ions in the second part p2 of the ion trap, that is to say, the addition of ions of the second cloud C2 to the already existing first ion cloud C1 confined in the second part p2 of the ion trap. Said method comprising the step 102 and the optional 103 also advantageously allows the sequential creation of a multi-species ion cloud, in the case where the ions of the first ion cloud C1 are of a first species, and the ions of the second ion cloud C2 are of a second species that is different from the first species.

**[0032]** Figure 2d schematically illustrates a step 104 of transferring the second ion cloud C2 from the first part p1 to the second part p2 by applying a potential variation on the central DC electrode Ec during a duration that is

less than 1 ms. The potential variation applied on said step 104 may typically be identical to the potential variation applied on said step 102. Alternatively, the potential variation applied on said step 104 may be different from the potential variation applied on step 102. The second ion cloud C2 is trapped in the first part p1 before said step 104 of transfer, and the second ion cloud C2 is trapped with the first ion cloud C1, forming a third ion cloud C3, in the second part p2 after said step 104 of transfer.

**[0033]** Steps 2c of introducing the second ion cloud C2 and 2d of transferring the second ion cloud C2 allow the accumulation of ions in the second part p2. Accumulation of ions may for example be useful in the case of rare ions or for "reloading" an ion cloud. Thanks to said steps 2c and 2d, rare ions may be progressively accumulated in order to obtain a large-size ion cloud and/or a high-density ion cloud that would have been difficult or impossible to obtain otherwise. Thanks to said steps 2c and 2d, an existing ion cloud having lost ions may be "refilled" or reloaded by replacing said lost ions. Such a refill may typically be useful in applications where multiple transfers of ion clouds are performed.

**[0034]** An optional step 105, illustrated on figure 3, of transferring the third ion cloud C3-that is made of the first ion cloud C1 and of the second ion cloud C2 - from the second part p2 to the first part p1 may then be performed by applying a potential variation on the central DC electrode Ec during a duration that is less than 1 ms. An optional step 105', illustrated on figure 3, of transferring the third ion cloud C3 from the first part p1 back to the second part p2 may then be performed by applying a potential variation on the central DC electrode Ec during a duration that is less than 1 ms. The third ion cloud C3 may thus be quickly transferred back and forth between the first part p1 and the second part p2, each transfer step during less than 1 ms.

**[0035]** Figure 3 is a diagram illustrating a sequence of the previously described steps of the method 100 of accumulating ions according to an aspect of the invention. Figure 3 shows:

- the step 101 of introducing or creating a first ion cloud C1 in the first part p1 of the ion trap 2 or in the first ion trap P1 of the double ion trap 1;
- the step 102 of transferring the first ion cloud C1 from the first part p1 to the second part p2 of the ion trap 2, or from the first ion trap P1 to the second ion trap P2 of the double ion trap 1;
- the optional step 102' of transferring the first ion cloud C1 from the second part p2 back to the first part p1, or from the second ion trap P2 back to the first ion trap P1;
- the optional step 103 of introducing a second ion cloud C2 in the first part p1 while the first ion cloud C1 is in the second part p2 of the ion trap 2, or in the first ion trap P1 while the first ion cloud C1 is in the second ion trap P2 of the double ion trap 1;

- the step 104 of transferring the second ion cloud C2 from the first part p1 to the second part p2, or from the first ion trap P1 to the second ion trap P2;
- the optional step 105 of transferring the third ion cloud C3 from the second part p2 to the first part p1, or from the second ion trap P2 to the first ion trap P1; and
- the optional step 105' of transferring the third ion cloud C3 from the first part p1 back to the second part p2, or from the first ion trap P1 to the second ion trap P2.

**[0036]** A particular embodiment of the method of accumulating ions according to an aspect of the invention is first described, that comprises an additional cooling of the ions. But it is to be noted that another particular embodiment of the method of accumulating ions according to an aspect of the invention is then described, that comprises no additional cooling of the ions - that is to say, no use of buffer-gas cooling or laser cooling or any other cooling mechanism, at any time of the process.

**[0037]** A monitoring protocol of the ion number in a trap has been developed in the context of the present invention and is now explained. Various applications have different experimental constraints. In a particular set-up, clouds of atomic ions of Ca<sup>+</sup> are created by photoionization, and laser-cooled. The fluorescence of the photons scattered in the laser-cooling process is recorded by a photomultiplier PM in photon-counting mode and an intensified CCD. The detection module is mounted on a slide, and ion clouds can be monitored in every trap by a translation of this slide. Collection efficiencies are identical, and the magnification of the optical set-up changes from 13.2 to 12.9 between both traps. Monitoring of the ion number is a central element for the evaluation of the transport efficiencies. In the case of larger ion ensembles, the photon-counting signal from a photomultiplier PM is not a reliable information as it will vary as a function of the cloud's temperature for fixed laser frequencies. The present monitoring protocol enables to enumerate the number of particles in the cloud with precision at any time, and guarantees higher fidelity.

**[0038]** An ion cloud containing more than a hundred atoms can be described by the model of the cold charged fluid, developed for non-neutral plasmas. It has been shown, that for temperatures below a few Kelvin, the density of the trapped ion ensemble is constant over its total size. This property is used here to infer ion numbers from the cloud size.

**[0039]** The cloud size can be determined with precision from the CCD images, when the ions are cooled to low temperatures undergoing a structural transition from a thermal gas to a correlated state. The recorded images then show an ellipse with a sharp contour edge. An automated fit procedure allows to measure both axis of the observed ellipse with high precision, resulting in an error bar of the ion number of less than 3%. The procedure is fast, and as it relies on a fitting procedure of the contour

of the cloud, it can still be applied when one of the axes of the ion cloud is larger than the observation zone.

**[0040]** Cooling to the correlated phase is done before and after every transport, during the transport the cloud is in the gas-state. In the particular embodiment here described, the applied transport function is a variation of hyperbolic-tangent shape of the applied DC voltage. For bandpass reasons, the shortest variation applied to the DC electrodes is 80  $\mu$ s.

**[0041]** Figure 4 shows:

- a first curve T1 of the fraction of ions of the first ion cloud C1 still present in the first part p1 after transfer, as a function of the duration of the transport function applied to the central DC electrode Ec, and
- a second curve T2 of the fraction of ions of the first ion cloud C1 present in the second part p2 after transfer, as a function of the duration of the transport function applied to the central DC electrode Ec.

**[0042]** Both the first curve T1 and the second curve T2 oscillate between 0 and 1, but for different transport duration values.

**[0043]** The large amplitude variations of the curve can be explained by the dynamics of the ion cloud. For a transport function, or potential variation, with a duration of 100  $\mu$ s when the first ion cloud C1 is in the first part p1, the complete first ion cloud C1 will leave the first part p1 for the second part p2. But for a transport function, or potential variation, with a duration of 180  $\mu$ s when the first ion cloud C1 is in the first part p1, 100% of the first ion cloud C1 remains at its original location - in the first part p1. The inventors have checked experimentally, by opening the second part p2 during the transport, and with numerical simulations, that this corresponds to a situation where the first ion cloud C1 has left the first part p1 during the transport, but was reflected in the second part p2, and came back to the first part p1. This behaviour can be reproduced numerically by small deviations of the trapping field from the ideal case, and the inventors assume that this is the experimental cause. For longer transport times, typically superior to 1 ms, only parts of the first ion cloud C1 come back to the first trap p1, as the central DC electrode Ec variation is not fast enough to confine the complete first ion cloud C1. The speed of transport has thus to be well adapted to the size and dynamics of the ion cloud.

**[0044]** The first curve T1 and the second curve T2 shown in figure 4 do not exactly overlap, even though the sizes of trap p1 and trap p2, or part sizes, the trapping parameters and the transfer protocol are identical. However, due to construction and the physical environment, and as a consequence of the fact that, in the particular embodiment described, ions are created in the first part p1, the first part p1 and the second part p2 show an asymmetry in response. Said asymmetry between the first part p1 and the second part p2 may be a potential asymmetry and/or a geometrical asymmetry. The inventors have

shown in numerical simulations that said asymmetry in response to transport can be introduced in ideal traps - that is, in traps having absolutely no geometrical asymmetry - by adding a small voltage to one of the rods of the trap - that is, by adding a potential asymmetry. Such an electric potential modifies the response of the transported ion cloud similar to the experimental observation.

**[0045]** The non-coinciding oscillations of the transfer probability illustrated in figure 4 have been used by the inventors to create a "no-return" transport protocol which allows to add ions from the first part p1 to the second part p2, without losing the cloud that may be already trapped in the second part p2. By choosing complementary points for the transport function duration of the two traps, a situation is created where ions are accumulated in a single trapping zone. For the conditions of figure 4, this corresponds for example to durations 300  $\mu$ s, 550  $\mu$ s and 780  $\mu$ s. At these durations, all the ions will leave the first part p1 and no ion will leave the second part p2. The values for maxima and minima depend on the trapping parameters, for example a variation in the voltage applied in the Z-direction generates a shift of the oscillations on the duration scale.

**[0046]** The resulting accumulation of ions is illustrated in figure 5 for various conditions of ion creation. Figure 5 reports the ion number in the second part p2 as a function of the transport cycle number for a fixed transport duration. For a given set of conditions, the ion cloud created in the first part p1 has a size of a few thousands ions. The ion cloud is transferred to the second part p2 and then the ion number is measured with the monitoring protocol previously described. After this, a new cloud is created in the first part p1 for the next transport cycle. Figure 5 shows:

- a first curve A1 of the number of ions in the second part p2 as a function of the number of accumulation cycles, for a 25-second creation step in the first part p1 and transport of the ion cloud;
- a second curve A2 of the number of ions in the second part p2 as a function of the number of accumulation cycles, for a 15-second creation step in the first part p1 and transport of the ion cloud.

**[0047]** The growth of the ion cloud in the second part p2 can be described as being linear for at least 10 cycles. For a large number of transport cycles, the ion ensemble seems to grow more slowly. This feature translates the limit of equilibrium conditions between the laser-cooling of the cloud and the RF heating as induced by the trap potential, and the start of a regime where the laser-cooling becomes less efficient. The observed deviation from a continuous linear growth rate is therefore a function of the trapping parameters and the applied laser intensity.

**[0048]** A true accumulation process is thus described, meaning that ions can be added from trap p1 to an already existing cloud in a trap p2. This is an important fact for all experiments where ions are rare or difficult to produce.

It allows to grow ion cloud in a pulsed regime by adding particles to an existing cloud. To the knowledge of the inventors, the large majority of existing experiments uses the term "accumulation" in different way as in the present document, for a variable integration time during initial creation or loading of a trap, which is a different creation process.

**[0049]** Being able to perform experiments without needing an additional cooling is an advantage in most cases. The inventors have realized a sequence of transport for ion clouds without laser cooling. The reported experiments are carried out under ultra-high vacuum conditions and in the absence of buffer-gas cooling, laser cooling or any other cooling mechanism. This is an important and significant step and progress for transporting charged particles, as the vast majority of experiments relies on buffer-gas cooling, as described in the previously cited patent US 2009/0058545 A1, or laser cooling during or after the transport in order to damp the transport-induced heating. Figure 6 schematically illustrates the cumulated ion number in the second ion trap as a function of the transfer cycle, without any cooling process, according to an aspect of the invention. Figure 6 shows:

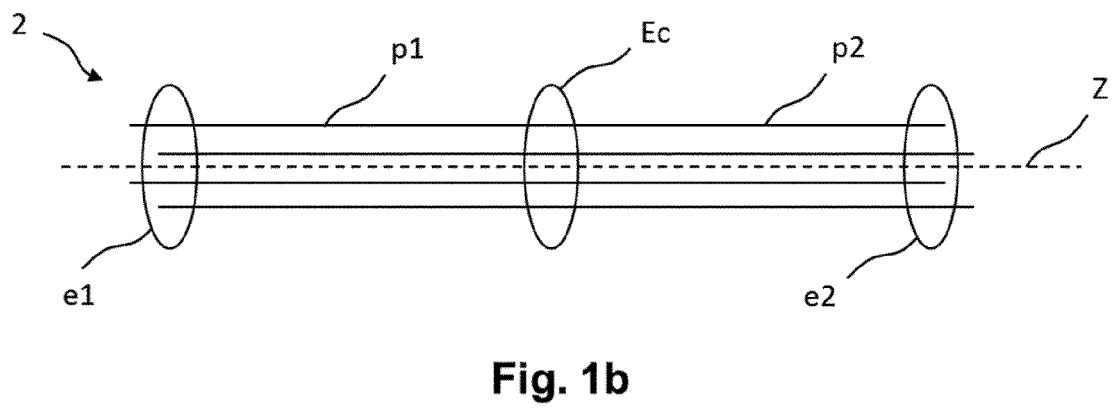
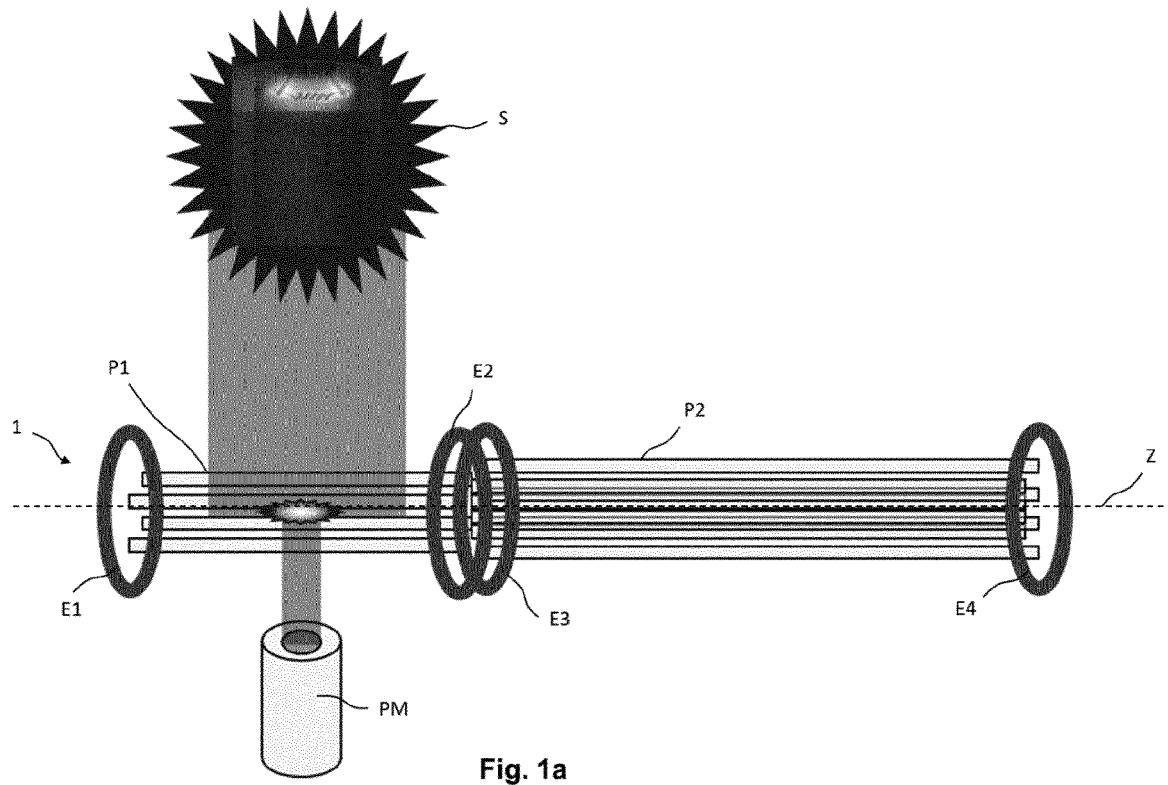
- dots D1 of the cumulated ion number in the second part p2 as a function of the transfer cycle number, without any cooling, for a cloud size of 1300 ions in the first part p1, and
- dots D2 of the cumulated ion number in the second part p2 as a function of the transfer cycle number, without any cooling, for a cloud size of 800 ions in the first part p1.

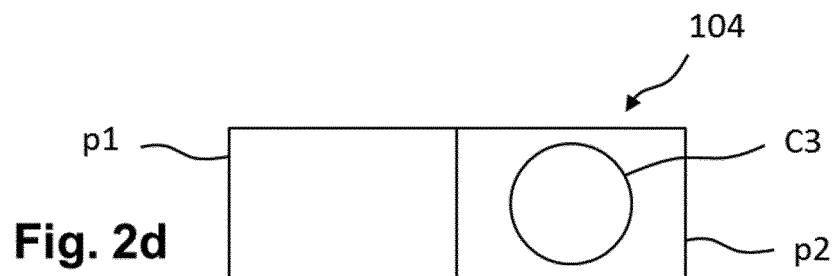
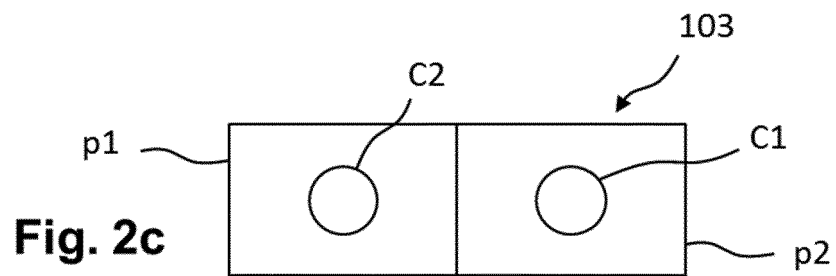
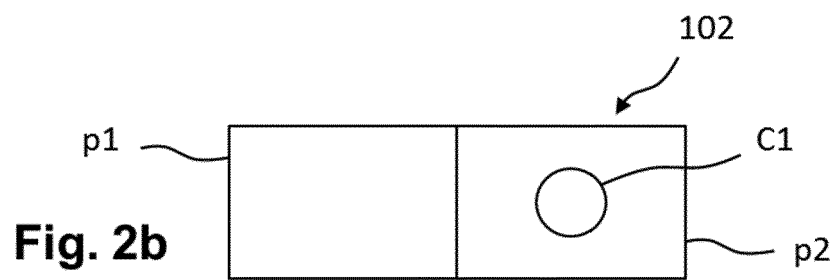
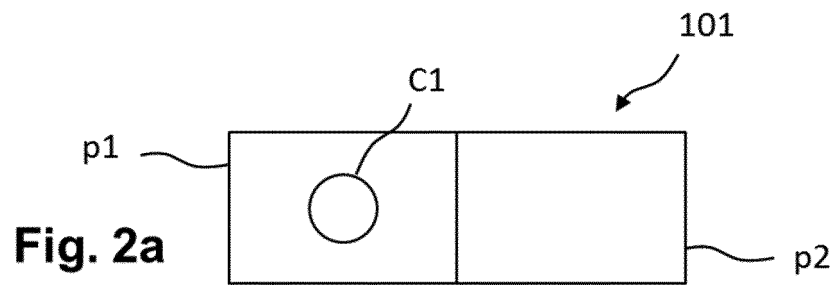
**[0050]** Figure 6 evidences a linear increase of the ion number in the second part p2 with the number of transport cycles, showing that the mechanism of transport is efficient even without the application of an additional cooling process.

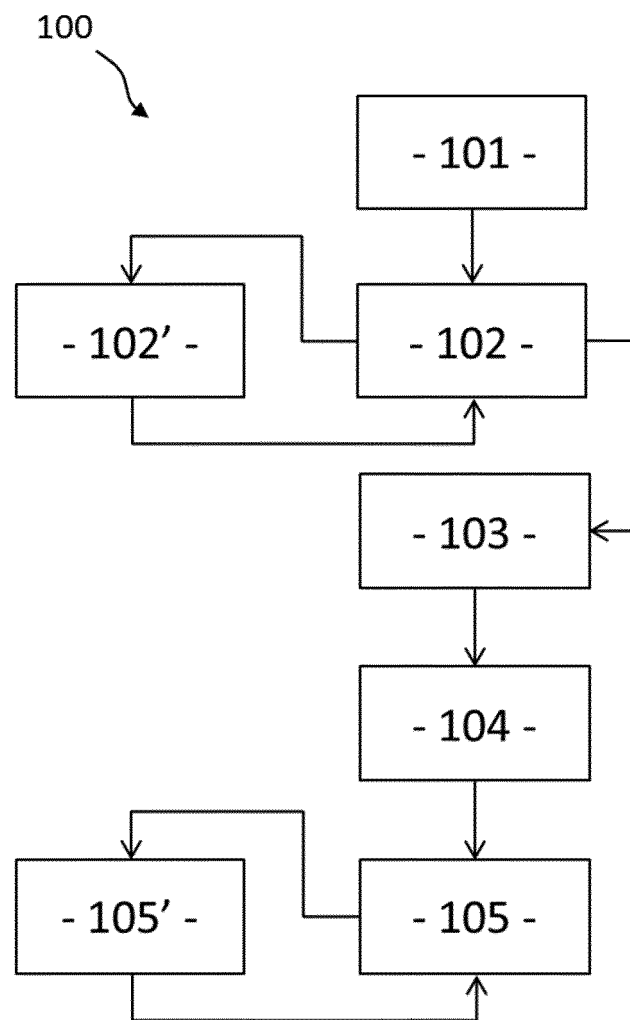
## Claims

1. A method (100) of accumulating ions in an ion trap (1, 2) having a first part (P1, p1) and a second part (P2, p2), the first and second parts being separated by a central electrode (E2-E3, Ec) and the first and second parts being asymmetrical, said method comprising a step (102) of transferring a first ion cloud (C1) from the first part to the second part by applying a potential variation on the central electrode during a duration that is less than 1 ms, the first ion cloud being trapped in the first part before said step of transfer and the first ion cloud being trapped in the second part after said step of transfer.
2. The method (100) of accumulating ions according to claim 1, wherein the method further comprises a step

- (102') of transferring back the first ion cloud (C1) from the second part (P2, p2) to the first part (P1, p1) by applying a potential variation on the central electrode (E2-E3, Ec) during a duration that is less than 1 ms, the first ion cloud (C1) being trapped in the second part (P2, p2) before said step (102') of transfer and the first ion cloud (C1) being trapped in the first part (P1, p1) after said step (102') of transfer.
3. The method (100) of accumulating ions according to claim 1, wherein the method further comprises:
- a step (103) of introducing a second ion cloud (C2) in the first part (P1, p1) of the ion trap (1, 2), and
  - a step (104) of transferring the second ion cloud (C2) from the first part (P1, p1) to the second part (P2, p2) by applying a potential variation on the central electrode (E2-E3, Ec) during a duration that is less than 1 ms, the second ion cloud (C2) being trapped in the first part (P1, p1) before said step (104) of transfer and the second ion cloud (C2) being trapped with the first ion cloud (C1) in the second part (P2, p2) after said step (104) of transfer.
4. The method (100) of accumulating ions according to the previous claim wherein the method further comprises a step (105) of transferring the first ion cloud (C1) and the second ion cloud (C2) from the second part (P2, p2) to the first part (P1, p1) by applying a potential variation on the central electrode (E2-E3, Ec) during a duration that is less than 1 ms, the first and second ion clouds (C1, C2) being trapped in the second part (P2, p2) before said step (105) of transfer, and the first and second clouds (C1, C2) being trapped in the first part (P1, p1) after said step (105) of transfer.
5. The method (100) of accumulating ions according to the previous claim wherein the method further comprises a step (105') of transferring the first ion cloud (C1) and the second ion cloud (C2) from the first part (P1, p1) back to the second part (P2, p2) by applying a potential variation on the central electrode (E2-E3, Ec) during a duration that is less than 1 ms, the first and second ion clouds (C1, C2) being trapped in the first part (P, p1) before said step (105') of transfer, and the first and second ion clouds (C1, C2) being trapped in the second part (P2, p2) after said step (105') of transfer.
6. The method (100) of accumulating ions according to any of the previous claims wherein a static potential asymmetry is created between the first part (P1, p1) and the second part (P2, p2) by introducing a static potential difference between the first part and the second part.
7. The method (100) of accumulating ions according to any of the previous claims wherein a geometrical asymmetry is created between the first part (P1, p1) and the second part (P2, p2) by choosing a first geometry for the first part and a second geometry that is different from the first geometry for the second part.
8. A device comprising:
- an ion trap (1, 2) having a first part (P1, p1) and a second part (P2, p2), the first and second parts being separated by a central electrode (E2-E3, Ec) and the first and second parts being asymmetrical, and
  - means for applying a potential variation on the central electrode (E2-E3, Ec) to transfer a first ion cloud (C1) from the first part to the second part by applying a potential variation on the central electrode during a duration that is less than 1 ms, the first ion cloud (C1) being trapped in the first part (P1, p1) before said transfer and the first ion cloud (C1) being trapped in the second part (P2, p2) after said transfer.
9. The device according to claim 7 wherein the first part (P1, p1) has a first static potential and the second part (P2, p2) has a second static potential that is different from the first static potential, the first and second parts being asymmetrical with a static potential asymmetry.
10. The device according to any of claims 7 and 8 wherein the first part (P1, p1) has a first geometry and the second part (P2, p2) has a second geometry that is different from the first geometry, the first and second parts being asymmetrical with a geometrical asymmetry.







**Fig. 3**

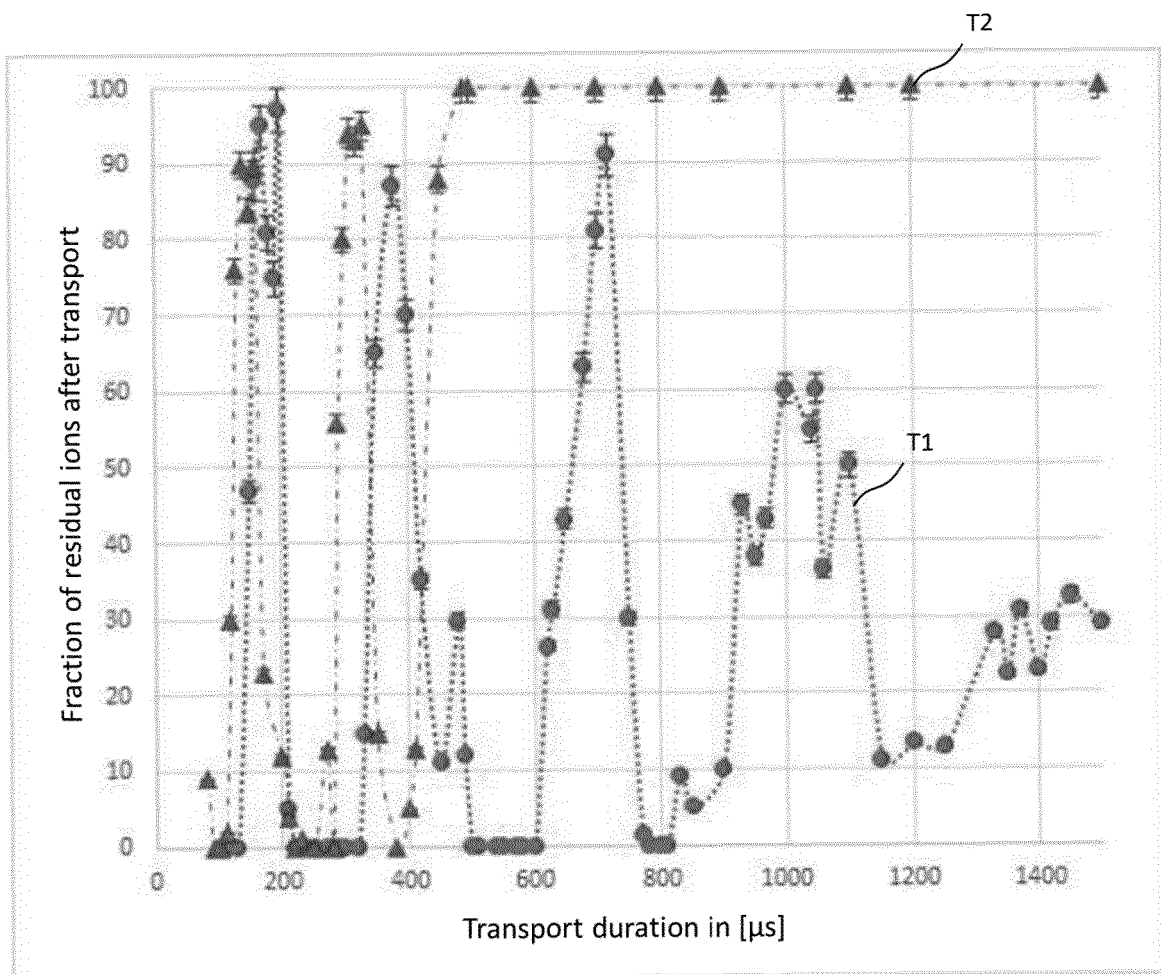


Fig. 4

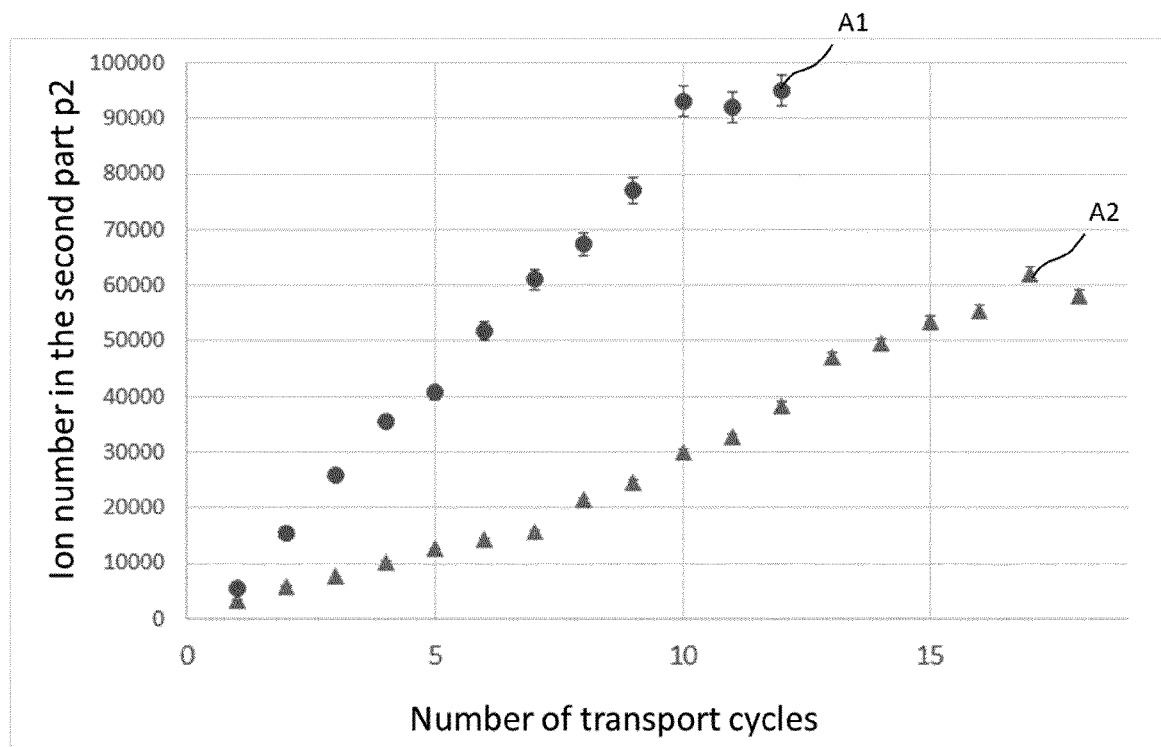


Fig. 5

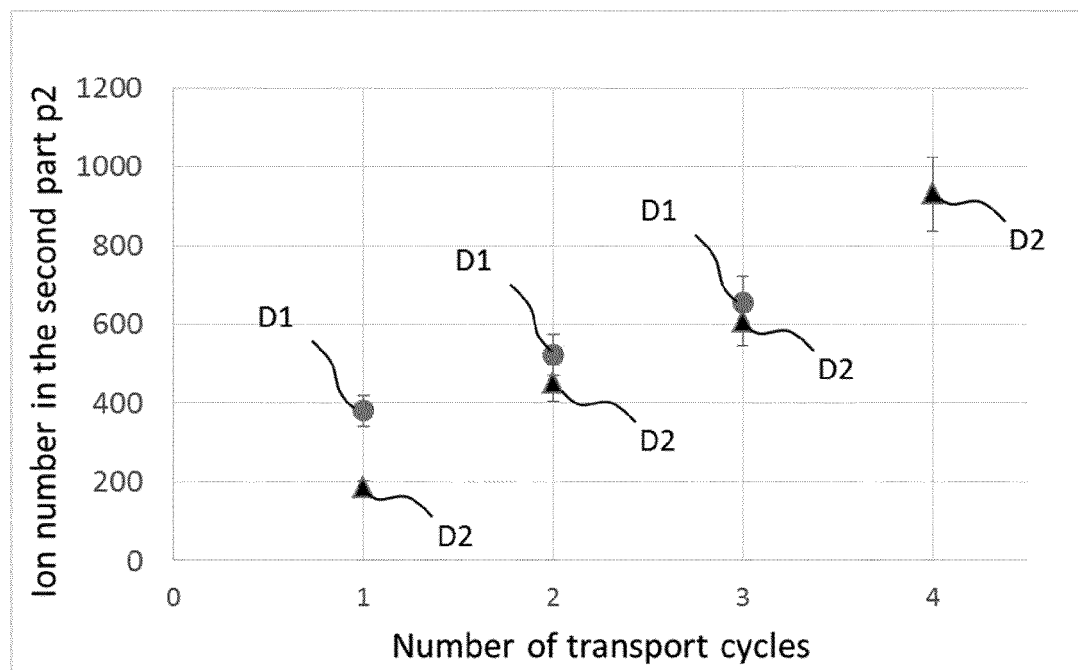


Fig. 6



## EUROPEAN SEARCH REPORT

Application Number  
EP 15 15 9063

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| 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                                                                                                                                                                                                                                                      | Jofre Pedregosa-Gutierrez ET AL: "Ion transport in macroscopic RF linear traps", Ft, 11 March 2014 (2014-03-11), XP055202079, Retrieved from the Internet: URL:http://arxiv.org/abs/1403.2568 [retrieved on 2015-07-13]<br>* abstract *<br>* page 10, paragraph 1 *<br>* page 19, paragraph 2 *<br>* figure 3 * | 1-10                                                                                                                                                                                                                                                                         | INV.<br>H01J49/42                       |
| A                                                                                                                                                                                                                                                      | -----<br>C. CHAMPENOIS ET AL: "A double ion trap for large Coulomb crystals", AIP CONFERENCE PROCEEDINGS, vol. 1521, 19 March 2013 (2013-03-19), pages 210-219, XP055202092, ISSN: 0094-243X, DOI: 10.1063/1.4796077<br>* abstract *<br>* page 217, paragraph 3 - page 218, paragraph 3 *<br>* figure 3 *       | 1,2,4-10                                                                                                                                                                                                                                                                     | TECHNICAL FIELDS SEARCHED (IPC)<br>H01J |
| A,D                                                                                                                                                                                                                                                    | -----<br>US 2009/058545 A1 (PRESTAGE JOHN D [US] ET AL) 5 March 2009 (2009-03-05)<br>* abstract *<br>* figure 4 *<br>* page 2, paragraph 0024 - page 2, paragraph 0025 *<br>-----                                                                                                                               | 1,2,4-10                                                                                                                                                                                                                                                                     |                                         |
| The present search report has been drawn up for all claims                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                              |                                         |
| Place of search<br>The Hague                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                 | Date of completion of the search<br>17 July 2015                                                                                                                                                                                                                             | Examiner<br>Dietsche, Rainer            |
| CATEGORY OF CITED DOCUMENTS<br>X : particularly relevant if taken alone<br>Y : particularly relevant if combined with another document of the same category<br>A : technological background<br>O : non-written disclosure<br>P : intermediate document |                                                                                                                                                                                                                                                                                                                 | T : theory or principle underlying the invention<br>E : earlier patent document, but published on, or after the filing date<br>D : document cited in the application<br>L : document cited for other reasons<br>& : member of the same patent family, corresponding document |                                         |

EPO FORM 1503 03.82 (P04C01)

17-07-2015

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

**REFERENCES CITED IN THE DESCRIPTION**

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