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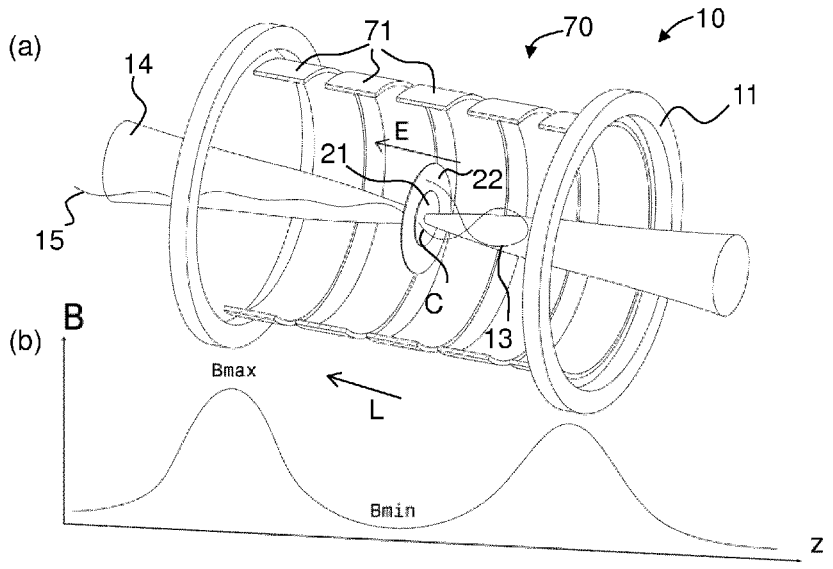

FIG. 5

(57) Abstract: An apparatus for moderation of positrons comprises a positron trap (10), a positron source arranged in the positron trap (10), and a moderator (22) arranged in the positron trap (10) in such a manner that positrons emitted from the positron source are able to repeatedly pass through the moderator (22) when they are confined in the positron trap (10). The positron source takes the form of a foil or mesh that is either identical with the moderator (22), or that is provided as a separate source foil (21) or source mesh arranged inside the positron trap. The positron source comprises at least one positron-emitting radioactive isotope or at least one isotope that can be transformed into a positron-emitting radioactive isotope in situ by bombardment with particles, or positrons are produced in the positron source by a pair- production process. After moderation, positrons are extracted axially with the aid of an electric field (E) created by an electrode structure (70).

[Continued on next page]

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TITLE

TRAP-ASSISTED MODERATION OF POSITRONS

TECHNICAL FIELD

The present invention relates to an apparatus for the moderation of positrons and to a corresponding method.

PRIOR ART

Relying on their unique sensitivity to the electronic environment, positrons are used in applied science for the characterization of materials. In such applications, a slow positron beam with energy spread of only a few electron volts (eV) is needed.

The most common and compact way to produce positrons is to use β+ emitters such as ^{22}Na, which emit positrons at kinetic energies in the keV to lower MeV range. To form a slow positron beam, the positrons are implanted in a moderator. Examples of moderator materials include metals, diamond and frozen rare gases. The positrons thermalize in the moderator material and are re-emitted with energies of a few eV. In such moderators only the low energy tail of the beta spectrum is available for the moderation process, which typically amounts to less than 1% of all positrons emitted from the source. This leads to a low efficiency of the moderation process, which typically is in the range between 10^{-4} and 10^{-3}. For the purpose of the present disclosure, moderation efficiency is defined as the number of moderated positrons per unit of time divided by the activity of the positron source. This low efficiency implies the use of strong positron sources in order to create a sufficiently strong slow positron beam. This limits the practical use of positron beams at

research institutions because of the high required activity of the positron sources, for which specific radio-safety guidelines must be observed. If rare gas moderators are employed, these moderators further require cryogenics, which results in high costs for building and maintaining the apparatus and is more complex in running the setup.

W.B. Waeber, M. Shi and D. Gerola, "High Efficiency Positron Moderation", *Materials Science Forum* Vols. 175-178 (1995) pp 115-124 discloses a cyclotron trap to slow down positrons. As the positrons spiral back and forth in the trap, they pass through a thin slow-down foil made of carbon and lose kinetic energy. This process is called premoderation. Once the positrons have slowed down to a few keV, they are extracted from the trap by application of an electric field and are implanted in a conventional moderator material for final moderation. The paper mentions in passing that the slow-down foil can in principle be used for both premoderation and final moderation. The device employed in those studies comprised several superconducting coils creating magnetic fields of up to 5 Tesla. Furthermore, two electrostatic mirrors were present at the end of the coils with applied potentials of 200 kV with the aim to create a nearly perfect confinement. The extraction of the positrons from the cyclotron trap was done with a very complex configuration of coils and electrodes. The paper is silent about the exact nature of the positron source. While the authors claim very high theoretical moderation efficiencies, actual moderation efficiencies achieved in this manner were rather low.

A very similar scheme is also disclosed in D. Gerola, W.B. Waeber, and M. Shi, "High efficiency positron moderation: a feasibility study of the slow beam confinement extraction", *Nuclear Inst. and Methods in Physics Research, A*, 364(1):33–43, 1995. The paper mentions that the slowing-down foil can be used for both premoderation and final moderation, and that moderated positrons can be extracted from the trap axially with the aid of a weak electric field.

M. Shi, W.B. Waeber, D. Gerola, U. Zimmermann, and D. Taqqu, "Premoderation of positrons - experiments on positron trapping and slowing-down", Nuclear Inst. and Methods in Physics Research, A, 349(1):8–14, 1994 also discloses the use of a cyclotron trap for moderating positrons. The positron source took the form of a dried $^{58}CoCl_2$ solution deposited on a thin carbon foil in the center of the trap.

Application of a radioactive solution to a foil requires special handling facilities. The use of a dried solution further entails a high risk of radioactive contamination of the trap and of its environment. In particular, it is disadvantageous to employ a dried solution under the high vacuum conditions required inside a positron trap, as radioactive material can reach the vacuum pump and can thus be distributed to the environment in an uncontrolled manner.

Related work was also published in the following papers:

- W.B. Waeber and M. Shi, "High performance hybrid slow positron beam and its user application spectrum", Applied surface science, 116:91–97, 1997;
- W.B. Waeber, M. Shi, D. Taqqu, U. Zimmermann, D. Gerola, F. Hegedüs, and L.O. Roellig, "Development of a high intensity low energy positron beam", The fifth international workshop on slow positron beam techniques for solids and surfaces, volume 303, pages 365–381, AIP Publishing, 1994;
- M. Shi, D. Gerola, W.B. Waeber, and U. Zimmermann, "Slow positron beam extraction from high magnetic fields", Applied surface science, 85:143–148, 1995;
- D. Gerola, W.B. Waeber, and M. Shi, "Design and simulation of the PSI electrostatic positron beam", Applied surface science, 85:106–110, 1995;
- D. Gerola, W.B. Waeber, M. Shi, and S.J. Wang, "Quasidivergency-free extraction of a slow positron beam from high magnetic fields", Review of Scientific Instruments, 66(7):3819–3825, 1995.

US 2014/0184061 A1 discloses an apparatus for moderation of positrons which comprises linear arrays of electrode and semiconductor structures of generally planar or cylindrical form. This setup is conceptually different from the positron trap disclosed by the above papers. In particular, no magnetic field is used to actively assist the moderation of positrons.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an apparatus for the moderation of positrons which provide high moderation efficiency while allowing a compact design of

the apparatus.

This object is achieved by an apparatus for moderation of positrons as laid down in claim 1. Further embodiments of the invention are laid down in the dependent claims.

The present invention provides an apparatus for the moderation of positrons, the apparatus comprising a positron trap, a positron source arranged in the positron trap, and a moderator arranged in the positron trap in such a manner that positrons emitted from the positron source are able to repeatedly pass through the moderator when they are confined in the positron trap. According to the invention, the positron source takes the form of a foil or of at least one mesh arranged inside the positron trap. The positron source can either be identical with the moderator (which then implies that the moderator itself is in the form of a foil or at least one mesh), or the positron source can include a separate source foil or source mesh arranged inside the positron trap.

By providing a positron source in the form of a foil or at least one mesh inside the trap, positrons can be produced exactly where they are needed, while contamination of the trap and of its environment is avoided. At the same time, the activity of the positron source can be minimized. It therefore may become possible to employ positron sources which have sufficiently low activity that less restrictive radiosafety regulations for the handling of the source apply. A positron source in the form of at least one mesh may be advantageous since meshes made of thin wires can be easier to produce than thin foils. Several meshes can be stacked to increase surface area and surface density of the positron source. Stacks of meshes have been proposed as moderators in traditional positron sources, see, e.g., Y. Nagashima et al., Jpn. J. Appl. Phys. Vol. 39 (2000) pp. 5356-5357.

The foil or at least one mesh that forms the positron source can comprise or consist of a source material that already includes at least one positron-emitting radioactive isotope, such as ^{22}Na, ^{48}V or ^{58}Co. In some embodiments, the source material is activated by implanting the positron-emitting radioactive isotope into the source material. In other embodiments, the positron-emitting radioactive isotope is created in the foil or mesh by activation, e.g. by bombardment with particles as described in more detail below. In such embodiments, the positron source is brought into the inside of the positron trap only after

having been activated. Importantly, the foil or at least one mesh that forms the positron source is itself made of a material in which the nuclei of the at least one positron-emitting radioactive isotope are embedded rather than being deposited on a foil in the form of a dried solution, as it is known from the prior art. In this manner, contamination of the trap and of its environment is avoided.

In other embodiments, the positron source can comprise or consist of a source material that includes at least one (preferably stable) isotope which can be transformed into a positron-emitting radioactive isotope inside the positron trap by bombardment with particles, such as ^{48}Ti (which is a stable isotope that can be transformed into ^{48}V by proton bombardment), ^{58}Ni (which is a stable isotope that can be transformed into ^{58}Co by exposure to a thermal neutron flux via the $^{58}Ni(n,p)^{58}Co$ nuclear reaction), or ^{27}Al (which is a stable isotope that can be transformed into ^{22}Na by proton bombardment via the $^{27}Al(p,X)^{22}Na$ nuclear reaction). This allows at least one positron-emitting radioactive isotope to be created in the material of the foil or mesh *in situ*. To this end, the apparatus can advantageously comprise a particle source (in particular, a particle accelerator) configured to create a particle beam that impinges on the positron source while the positron source is arranged within the positron trap, the particle beam acting to create at least one positron-emitting radioactive isotope inside the positron source by a nuclear reaction. The particle source can be, in particular, a proton accelerator that creates a proton beam.

In yet other embodiments, the positron source can be configured to produce positrons by a pair production process. To this end, the apparatus can comprise a particle source configured to create a particle beam that impinges on the positron source while the positron source is arranged within the positron trap so as to create electron-positron pairs in the positron source by bremsstrahlung. The particle beam is preferably an electron beam with a kinetic energy well above the pair-production threshold (1.022 MeV), which can be produced by a suitable electron accelerator. Pair production is particularly efficient if the material of the positron source, which here acts as the pair-production target, contains comparatively heavy nuclei. Since also some of the materials that are known to be efficient positron moderators contain heavy nuclei, the creation of positrons by pair production inside the moderator itself can be very efficient. For instance, tungsten is known to be an

efficient positron moderator, but is also an efficient pair-production target.

If the positron source is in the form of a foil, the thickness of the positron source is preferably less than 2 micrometers, more preferably 1 micrometer or less. If the positron source is in the form of a mesh or of a stack of meshes, preferably the mesh or meshes are made of wires having a diameter of 20 micrometers or less.

Advantageously the positrons are not only slowed down in the moderator by repeatedly passing through the moderator (and possibly through the separate source foil or mesh, if the positron source is not identical with the moderator), but the moderator comprises a material that allows positrons to be implanted into the moderator after having been slowed down, to be thermalized by the moderator material, and to be re-emitted from the moderator after having been thermalized. Suitable moderator materials include tungsten (W), nickel (Ni), molybdenum (Mo), iridium (Ir), copper (Cu), platinum (Pt), rhenium (Re), gold (Au), rhodium (Rh), silver (Ag), palladium (Pd), and silicon carbide (SiC). The apparatus is then further configured to extract thermalized positrons from the positron trap after they have been re-emitted from the moderator foil.

If the moderator is in the form of a foil, it is advantageous if the moderator foil is monocrystalline. This increases the diffusion length of the positrons in the foil material. However, polycrystalline foils can also be employed. In some embodiments, the moderator foil can have a two-layer configuration, with a moderator layer made of a moderator material and a source layer made of a material that comprises a positron-emitting radioactive isotope or an isotope that can be transformed into a positron-emitting radioactive isotope by bombardment with particles. For instance, the moderator foil can have a moderator layer made of tungsten (W), nickel (Ni), or molybdenum (Mo), and a source layer comprising ^{48}V (which is a positron-emitting radioactive isotope) or ^{48}Ti (which is a stable isotope that can be transformed into ^{48}V by proton bombardment). The moderator layer can be applied to the source layer, or vice versa, by a vapor deposition technique. Importantly, the source layer is an integral component of the moderator, meaning that it cannot be removed without destroying the moderator.

The apparatus can comprise an electrode structure for generating an electric field along the

longitudinal axis of the positron trap for aiding axial extraction of the thermalized positrons from the positron trap. Axial extraction with the aid of an electric field is advantageous due to its simplicity. In order to generate the electric field, the apparatus can further comprise a voltage source connected to the electrode structure.

In some embodiments, the electrode structure comprises a grid (i.e., a mesh that can be subjected to an electric potential difference relative to the moderator) arranged at an axial distance from the moderator.

In order to support the grid, the moderator, and possibly the separate source foil or source mesh inside the positron trap, the apparatus can comprise a frame. The moderator can be suspended in said frame by at least two moderator-carrying wires extending in parallel across the frame, and the grid can be suspended in said frame by at least two grid-carrying wires extending in parallel across the frame, the grid-carrying wires extending advantageously across the moderator-carrying wires, in particular, perpendicular to the moderator-carrying wires.

In other embodiments, the electrode structure comprises a plurality of concentric annular electrodes arranged sequentially along the longitudinal axis. The annular electrodes can be connected to a voltage source in such a manner that each electrode is at a different potential, the potential preferably varying monotonically along the longitudinal axis. In this manner, the electric field distribution can be tailored so as to optimize the extraction of the positrons from the trap.

The use of an electrode structure comprising a plurality of annular electrodes for extracting the moderated positrons is also advantageous if the positron source takes a different form than the form of a foil or mesh. The present invention therefore also encompasses an apparatus for moderation of positrons, the apparatus comprising a positron trap, a moderator arranged in the positron trap in a manner that positrons repeatedly pass through the moderator when they are confined in the positron trap, and an electrode structure for generating an electric field along a longitudinal axis of the positron trap for aiding axial extraction positrons from the positron trap after they have been moderated inside the positron trap, wherein the electrode structure comprises a plurality of concentric annular

electrodes arranged sequentially along the longitudinal axis.

The positron trap can define a trap center, a central longitudinal axis and a central plane that extends perpendicularly to the longitudinal axis and contains the trap center. In advantageous embodiments, the positron source is arranged near the trap center or essentially at the trap center. It can advantageously extend parallel to the central plane.

In preferred embodiments, the positron trap is a cyclotron trap. A cyclotron trap comprises a magnetic field source configured to create a static magnetic field that has cylindrical symmetry about a central longitudinal axis. The magnetic field has a local minimum at the trap center and two equal maxima on the longitudinal axis at equal distances from the trap center. There are various possibilities for creating such a magnetic field distribution. In the simplest case, two identical coils carrying identical DC currents are arranged at a distance along the longitudinal axis, the distance being larger than their radius. In other embodiments, more than two coils can be employed. In yet other embodiments, a single, long (i.e., length larger than diameter) solenoid coil can be employed, and the field distribution can be shaped with the aid of magnetic materials arranged inside and/or outside the coil. Instead of using coils, it is also possible to employ permanent magnets. Numerous other possibilities exist. The positron trap can additionally employ an electric field, e.g., by including one or more electrostatic mirrors. The present invention is not limited to the use of cyclotron trap, and other types of traps that are configured to confine positrons within the trap can be employed.

In order to transport the extracted slow positrons to a region of low magnetic field while minimizing divergence of the positron beam, the apparatus can comprise at least one guiding coil that extends away from the positron trap along the longitudinal axis, the guiding coil being configured to guide thermalized positrons into a region outside the positron trap after the positrons have been extracted from the positron trap. Preferably the guiding coil extends into a region where any magnetic field that originates from the positron trap (not taking into account the field of the guiding coil itself) is below 10 mT, preferably below 1 mT.

The apparatus will generally further include a vacuum chamber, and the positron trap will

be arranged inside the vacuum chamber. The vacuum chamber will then have an extraction opening for extracting the positrons from the trap. It is then preferred that a vacuum tube extends away from the extraction opening along the longitudinal axis, the vacuum tube housing the guiding coil.

The present invention further provides a related method of moderating positrons. The method comprises:

creating positrons inside a positron trap;

confining the positrons in the positron trap; and

slowing down the positrons by repeatedly passing the positrons through a moderator.

The positrons are created in a positron source in the form of a foil or of at least one mesh inside the positron trap, the positron source being either identical with the moderator or including a separate source foil or source mesh arranged inside the positron. The positron source can comprise a source material that already includes at least one positron-emitting radioactive isotope or that includes at least one isotope that can be transformed into a positron-emitting radioactive isotope *in situ* by bombardment with particles, or the positron source can be configured to produce positrons by a pair production process.

Accordingly, the method can comprise bombarding the positron source inside the positron trap with a particle beam, thereby creating at least one positron-emitting radioactive isotope or electron-positrons pairs in the material of the positron source *in situ*.

The method can further comprise implanting positrons into the moderator after having been slowed down, allowing the positrons to thermalize in the moderator, and extracting thermalized positrons from the positron trap after they have been re-emitted from the moderator.

Advantageously, thermalized positrons are extracted from the positron trap along a longitudinal axis of the positron trap with the aid of an electric field. Optionally the extracted positrons are guided to a region outside the positron trap by at least one guiding coil that extends along the longitudinal axis.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention are described in the following with reference to the drawings, which are for the purpose of illustrating the present preferred embodiments of the invention and not for the purpose of limiting the same. In the drawings,

Fig. 1 shows a schematic sketch illustrating the working principle of an apparatus for the moderation of positrons according to a first embodiment of the present invention (part (a)) and the resulting magnetic field distribution along the longitudinal axis (part (b));

Fig. 2 shows a perspective partial sectional view of an apparatus for the moderation of positrons according to a first embodiment of the present invention, parts of the vacuum chamber being cut away for better visibility;

Fig. 3 shows an enlarged detail view of the apparatus in Fig. 2;

Fig. 4 shows an enlarged detail view of a carrier assembly of the apparatus in Figs. 2 and 3;

Fig. 5 shows a schematic sketch illustrating the working principle of an apparatus for the moderation of positrons according to a second embodiment of the present invention (part (a)) and the resulting magnetic field distribution along the longitudinal axis (part (b));

Fig. 6 shows a perspective partial sectional view of an apparatus for the moderation of positrons according to a second embodiment of the present invention, parts of the vacuum chamber being cut away for better visibility;

Fig. 7 shows a perspective partial sectional view of the electrode subassembly of the apparatus in Fig. 6; and

Fig. 8 shows an exploded view of the electrode subassembly in Fig. 7.

DESCRIPTION OF PREFERRED EMBODIMENTS

<u>First embodiment: extraction with grid</u>

The general working principle of an apparatus for the moderation of positrons according to

a first embodiment of the present invention is schematically illustrated in Figure 1, part (a).

A key component of the apparatus is a cyclotron trap, also called a magnetic bottle. Two identical coils 11, 12 are arranged symmetrically from the trap center C on a common central axis extending in a longitudinal direction L. The coils are separated by a distance that is larger than their radius. They carry identical electric DC currents, thereby creating an inhomogeneous static magnetic field. The resulting static magnetic field distribution along the central longitudinal axis is shown in part (b) of Figure 1. The field distribution has a local minimum Bmin at the trap center C and two equal maxima Bmax at the center of each coil. Charged particles are trapped in the inhomogeneous magnetic field, performing a spiraling motion back and forth between the two coils, if the momentum $p_\perp$ perpendicular to the longitudinal axis and the momentum $p_\parallel$ parallel to the longitudinal axis fulfill the following requirement when the particle traverses the central plane of the trap (i.e., a plane perpendicular to the longitudinal direction L that comprises the trap center C):

$$\left|\frac{p_\parallel}{p_\perp}\right| \leq \sqrt{\frac{Bmax}{Bmin} - 1}$$

This equation defines a region in momentum space which is outside the so-called loss cone 14. The loss cone 14 is the portion of momentum space for which no trapping is possible in the cyclotron trap.

The positrons are created in a thin source foil 21 placed near the center C of the trap, e.g., an activated metal foil that contains a positron-emitting radioactive isotope (β+ emitter) such as ^{22}Na, ^{48}V or ^{58}Co. The source foil 21 extends parallel to the central plane of the trap and orthogonal to the longitudinal direction L. A moderator 22 in the form of a thin moderator foil made, e.g., of tungsten (W), or in the form of a stack of meshes made of a moderator material like tungsten is also placed near the center C of the trap, likewise extending parallel to the central plane of the trap. The trapped positrons repeatedly pass through the source foil 21 and the moderator 22 when they spiral back and forth through trap and lose energy each time they pass through the foils and possibly meshes. Once their remaining kinetic energy is below a few keV, the positrons can be captured by the material

of the moderator ("implanted" in the moderator), can thermalize in the moderator, and can be re-emitted as slow positrons with a well-defined narrow energy distribution in the eV range. These slow positrons are then extracted from the trap. Of course, a certain proportion of positrons annihilates in the process.

If the moderator is in the form of a foil, the moderated positrons are generally emitted from the surface of the moderator foil with a forward trend and therefore have an increased probability to have a momentum vector inside the loss cone so as to satisfy the condition to escape from the trap. In this manner, an essentially mono-energetic slow positron beam can be directly formed.

To enhance the efficiency of the extraction of the moderated positrons, an electric field is created such that the re-emitted positrons gain additional axial momentum. In the setup of Fig. 1, a grid 23 is provided for this purpose. The grid is positioned near the moderator 22 and parallel thereto (i.e., with its surface normal parallel to the longitudinal direction L). An electric voltage is applied between the moderator and the grid so as to create an electric field E between the moderator and the grid, the electric field being oriented essentially parallel to the longitudinal direction L. In this manner it becomes possible to extract a large proportion of the thermalized positrons from the trap along the longitudinal direction (see exemplary positron path 15).

Figures 2 and 3 illustrate an exemplary embodiment of an apparatus for creating a beam of moderated positrons along the principles illustrated in conjunction with Figure 1. The apparatus comprises a pair of magnet coils 11, 12 to create an inhomogeneous magnetic field inside a vacuum chamber 40, as described above in conjunction with Figure 1. A vacuum pump 50 is connected to a suction opening 42 of vacuum chamber 40 to evacuate the inside of vacuum chamber 40.

As apparent from Fig. 3, a moderator 22 in the form of a thin moderator foil or in the form of one or more meshes, as well as a grid 23 are placed parallel to one another near the center of the trap with the aid of a carrier assembly 20, which is shown by itself in Figure 4. The carrier assembly 20 comprises a frame 24 made of an electrically conducting material. A pair of two parallel foil-carrying wires 25 traverses the frame 24 horizontally.

The moderator 22 is suspended between these wires in the center of the frame. Thereby the moderator foil is electrically connected to the frame 24, being always at the same electric potential as the frame 24. The grid 23 is suspended from a pair of two parallel grid-carrying wires 26, which traverse the frame 24 vertically. These wires are mounted to the frame 24 via insulator bushings 27, thereby being electrically insulated from the frame 24. As schematically shown in Fig. 3, the frame is mounted inside the vacuum chamber 40 with the aid of electrically insulating studs 28. Thereby, the frame 24 and the moderator 22 can be put at a desired electrical potential level, e.g., they can be electrically grounded. A first electric wire 29 connects to the frame 24, while a second electric wire connects to the grid-carrying wires 26. Thereby, a voltage can be applied between the moderator 22 (at a first potential, e.g., at electric ground) and the grid 23 (at a second potential, e.g., a variable potential). In Fig. 3, the wires 29 are shown only in a highly schematic fashion, extending through an access opening 43 of the vacuum chamber 40. In reality, this opening would be closed by a suitable closure in a vacuum tight-manner, and a vacuum feed-through would be provided for the wires to enable application of the voltage from outside the vacuum chamber.

As schematically illustrated in Figure 2, a particle accelerator 30, e.g., a proton accelerator, creates a particle beam 31 that impinges on moderator 22, thereby creating β+ emitters in the moderator 22 *in situ*. The moderator thereby also acts as a source. Instead, a separate source foil or mesh can be provided in parallel to the moderator 22, the source foil/mesh acting as the target for the particle beam 31. The particle accelerator 30 and the particle beam 31 are shown in Figure 2 only in a highly schematic manner. In reality, suitable beam guiding elements would be present to direct the particle beam to the foil surface. Such elements are known in the art. Instead of creating β+ emitters in the moderator 22 by bombardment with nuclei like protons or other comparatively heavy particles, it is also possible to bombard the moderator or the source foil/mesh with light particles like electrons to create electron-positron pairs by bremsstrahlung inside the material of the moderator or of the source foil/mesh.

In operation, identical DC currents are fed to the coils 11 and 12, and the particle beam 31 creates short-lived β+ emitters or electron-positron pairs in the moderator 22 or in the source foil/mesh. Positrons are thereby created in the moderator 22 or in the source

foil/mesh. That portion of positrons that is emitted with a momentum vector outside the loss cone 14 will be trapped by the magnetic field created by coils 11 and 12 and travel back and forth through the trap, repeatedly passing through the moderator 22 and, if applicable, through the source foil/mesh. Thereby, the positrons lose energy until they are implanted in the moderator. After moderation, they are re-emitted and are extracted along the longitudinal direction L. This process is supported by the application of a DC electric field by applying a negative DC voltage between the grid 23 and the moderator 22. The positrons leave the trap through an extraction opening 41 and enter a long guiding coil 60, which guides the positrons into a low-field region (e.g., less than 1 mT) remote from the cyclotron trap, where they are ready to be used in the desired experiments. It goes without saying that guiding coil 60 is housed in a vacuum tube (not shown in Figures 2 and 3), and that guiding coil 60 may be much longer than shown in Figures 2 and 3.

Example

A setup similar to the setup shown in Figures 2-4 was constructed. A titanium (Ti) foil with a thickness of 1 micrometer was irradiated with 8 MeV protons from the ETH Zurich TANDEM accelerator to create ^{48}V nuclei, which are β+ emitters. At the time of the experiment the positron activity was 3.24 kBq. This foil was employed as a source foil. A monocrystalline tungsten (W) moderator foil with a thickness of 1 micrometer, oriented such that the (110) direction was parallel to the surface normal of the foil, was purchased from the Dept. of Physics and Astronomy of the University of Aarhus from Denmark and annealed 2 × 15 min through electron bombardment shortly before mounting. For the extraction a 96% transmission tungsten (W) grid was used. The activated Ti foil, the W foil and the W extraction grid were mounted near the trap center in such a manner that they were oriented parallel to each other and that their respective surface normal intersected the central longitudinal axis of the cyclotron trap.

For creating the static magnetic field of the cyclotron trap, two identical water-cooled hollow square copper tube coils were used. The maximum field on the central axis of the cyclotron trap was Bmax = 0.2559(2) T, and the local minimum at the center was Bmin = 0.0544(2) T at a current of 650 A. Assuming an isotropic emission of fast positrons from the source and a magnetic field ratio of 4.704(17), the trap was expected to maximally

confine 60.89(12)% of the positrons.

Positrons were slowed down in the trap by repeatedly passing through the moderator foil and the source foil, were thermalized in the moderator foil and were re-emitted from its surface at a kinetic energy of $E_{\parallel \mathrm{mod}} = 3 \pm 0.8$ eV. For extraction, a negative voltage of up to -100 V was applied between the grid and the moderator foil. To perform the detection in a low field region (< 0.5 mT), a 1 m long 10 mT solenoid guiding coil guided the positrons away from the trap. The magnetic field of the guiding coil was terminated with a mu metal shielding. The extracted positrons were detected with an electron multiplier.

The extraction grid does not only support the formation of the slow positron beam but also offers the possibility to reverse this effect and provide a tool to measure the moderation efficiency. The positrons escaping the trap are a mixture of fast positrons with energies in the keV range and the slow, moderated, ones with eV energy. Reversing the voltage between the moderator foil and the grid blocks all slow positrons while still allowing the fast positrons to exit the trap. The difference in the number of positrons escaping the trap for these two configurations is the number of slow, moderated positrons.

To assess the performance, a detailed simulation was carried out with Geant4. The trap was implemented on the basis of magnetic field maps created with COMSOL and Matlab. Simulation of the extraction with an applied voltage of -100V between grid and moderator suggested an extraction efficiency of nearly 100%. When the grid and the moderator are kept at the same potential, the amount of slow positrons escaping from the trap depends on the spread in emission energy, e.g. for 3 ± 0.8 eV only ≈ 50% will reach the detector. With application of a reversed voltage of +100V ("blocking mode"), no moderated positrons will escape. The proportion of fast positrons contributing to the background was expected to be below 10^{-4}. The simulation predicted a moderation efficiency of $\approx 10^{-2}$ for the setup discussed above. Further simulations with optimized parts suggested that efficiencies in the order of 10^{-1} should be achievable.

The experimental results are listed in Table I. The division of the counts in the extraction mode by the total activity gives a moderation efficiency of $\epsilon \approx 1.5 \times 10^{-2}$. Considering that the complex physics of the moderation process is not included, the simulation results

are in fair agreement with the experimental results. Going from extraction to same potential mode the counts are halved both in experiment and in simulation. This does not only show that the idea of the cyclotron trap assisted moderation works, but also that the established simulation suite can be used to estimate the efficiency and optimize the parameters of the apparatus. It is expected that efficiencies in the range of 10-20% can be achieved.

TABLE I. Simulation and experimental results of the count rates in the detector for the background (bkg), blocking (blk), equal potential (eql) and extraction (ext) settings.

	bkg	blk	eql	ext
Simulation (s^{-1})	0.3	0.3	19	38
Experiment (s^{-1})	1	1	24	50

In a modification, a stack of moderator meshes can be employed instead of a moderator foil. In a traditional setup without a positron trap, good results were achieved with a stack of 12 meshes, each mesh being made of tungsten wires with a thickness of 12.5 micrometers and a transmission (i.e., ratio of area without moderator material to total area if viewed perpendicular to the plane of the mesh) of 92%. Each mesh had a size of 1 cm x 1 cm. The stack had a thickness of approximately 0.5 mm. The stack can be suspended in the frame and employed as a moderator in a positron trap in the same manner as a moderator foil.

Second embodiment: ring electrodes

The working principle of a second embodiment is illustrated in Figure 5. Elements that have the same or a similar function as in the first embodiment are provided with the same reference signs as in Figures 1-4.

The key difference to the first embodiment is the manner in which an electric field is created for facilitating extraction of the thermalized positrons. While in the first

embodiment a grid is employed for this purpose, the second embodiment uses an electrode subassembly 70, which comprises a number of annular electrodes (ring electrodes) 71 arranged concentrically around the central longitudinal axis in a sequence along this axis. In this manner, the electric field distribution can be exactly tailored. In particular, it becomes possible to generate a highly homogeneous electric field, which helps to reduce the divergence of the resulting positron beam.

Figure 6 shows an exemplary embodiment of an apparatus according to the second embodiment. The general setup is similar to the setup of the apparatus of the first embodiment, and identical or similar elements are provided with the same reference signs as in Figures 1-4. Portions of the apparatus according to the second embodiment are illustrated in greater detail in Figures 7 and 8.

In the present example, the electrode subassembly 70 comprises five ring electrodes 71 of equal dimensions, equally distributed along the central longitudinal axis of the trap to create a chain of ring electrodes. The ring electrodes 71 are mounted on supporting bars 72, being electrically insulated from the supporting bars by insulator bushings 76. The ring electrodes 71 are connected in a series configuration by ohmic resistors 73, which act to create a uniform potential distribution between the electrodes when a voltage is applied to the first and the last electrode in the chain with the aid of wires 74 (shown only in Figure 6 in a highly schematic manner). For instance, if a voltage of 100 V is applied between the first and last electrodes, the voltage difference between neighboring electrodes will always be 25 V.

The central electrode is provided with a horizontal hinge and a latch 75 to enable simple access to the center of the trap.

The moderator 22 and possibly the source foil/mesh are mounted in a carrier subassembly 80, which comprises an annular frame 81 connected to a circular end plate 82 by supporting rods 83 which extend along the longitudinal direction L. A pair of moderator-supporting wires 25 traverses the frame 81, the moderator 22 being suspended in the center of the frame 81 by the wires 25. The wires are electrically insulated from those portions of the frame 81 that touch the central electrode of the electrode subassembly 70. The carrier

subassembly 80 has a somewhat reduced diameter, allowing the carrier subassembly 80 to be axially pushed into the electrode subassembly 70. An end rod 84 extends axially away from the end plate 82 to facilitate removal of the carrier subassembly 80 from the electrode subassembly 70.

The electric field created by electrode subassembly 70 is highly homogeneous, allowing an improved extraction of positrons at minimum divergence.

Modifications

Many modifications are possible without leaving the scope of the present invention. In particular, the moderator can be in the form of a foil that has a two-layer structure. In this case, the foil can comprise a moderator layer made of a moderator material, e.g., tungsten as in the above example, and a separate source layer that contains a positron-emitting radioactive isotope or an isotope that can be transformed into a positron-emitting radioactive isotope by bombardment with particles. For instance, the source layer may be made of titanium, and the stable titanium isotope ^{48}Ti can be transformed into the positron-emitting radioactive isotope ^{48}V by proton bombardment. The source layer can be applied to the moderator layer by vapor deposition, or vice versa.

In other embodiments, the moderator is made of a homogeneous material, without an additional layer, and said material itself comprises an isotope that can be transformed into a positron-emitting isotope by bombardment with particles. An example would be a moderator made of nickel, which can be transformed into the positron-emitting radioactive isotope ^{58}Co by exposure to a thermal neutron flux via the ^{58}Ni(n,p)^{58}Co nuclear reaction.

In still other embodiments, two separate foils are provided: a source foil and a moderator foil. Both foils can be arranged in a stacked, parallel configuration. They can be suspended in a common frame by wires.

While in the above embodiments the positrons are confined in the trap purely by the action of a static magnetic field, the magnetic field can be augmented by electric fields to improve confinement in the trap, e.g., by the provision of electrostatic mirrors. Instead of

employing two coils for creating the magnetic field, more than two coils or even permanent magnets can be employed.

Many other modifications are possible without leaving the scope of the present invention, and it is to be understood that the present invention is not limited to the above examples.

LIST OF REFERENCE SIGNS

10	cyclotron trap	43	access opening
11	1st magnet	50	vacuum pump
12	2nd magnet	60	guiding coil
13	positron path	70	electrode subassembly
14	loss cone	71	annular electrode
15	positron path	72	supporting bar
20	carrier assembly	73	resistor
21	source	74	electric wires
22	moderator	75	latch
23	grid	76	insulator bushing
24	support frame	80	carrier subassembly
25	foil-carrying wires	81	frame
26	grid-carrying wires	82	end plate
27	insulator bushing	83	supporting rod
28	insulating stud	84	end rod
29	electric wires	L	longitudinal direction
30	particle accelerator	C	trap center
31	particle beam	B	magnetic field
40	vacuum chamber	Bmin	minimum of magnetic field
41	extraction opening	Bmax	maximum of magnetic field
42	suction opening	E	electric field

CLAIMS

1. An apparatus for moderation of positrons, the apparatus comprising:

a positron trap (10);

a positron source arranged in the positron trap (10); and

a moderator (22) arranged in the positron trap (10) in a manner that positrons emitted from the positron source are able to repeatedly pass through the moderator (22) when they are confined in the positron trap (10),

characterized in that the positron source is in the form of a foil or at least one mesh, the positron source being either identical with the moderator (22) or including a separate source foil (21) or source mesh arranged inside the positron trap.

2. The apparatus of claim 1, wherein the positron source comprises at least one positron-emitting radioactive isotope.

3. The apparatus of claim 1, wherein the positron source comprises at least one isotope that can be transformed into a positron-emitting radioactive isotope *in situ* by bombardment with particles, and

wherein the apparatus preferably further comprises a particle source (30) configured to create a particle beam (31) that impinges on the positron source while the positron source is arranged within the positron trap (10) so as to create at least one positron-emitting radioactive isotope in the positron source *in situ*.

4. The apparatus of claim 1, wherein the apparatus comprises a particle source (30) configured to create a particle beam (31) that impinges on the positron source while the positron source is arranged within the positron trap (10) so as to create electron-positron pairs in the positron source *in situ*.

5. The apparatus of any one of the preceding claims, wherein the moderator (22) comprises a moderator material that allows positrons to be implanted into the moderator after having been slowed down by repeatedly passing through the

moderator (22), to be thermalized by the moderator material, and to be re-emitted from the moderator (22) after having been thermalized.

6. The apparatus of any one of the preceding claims, comprising an electrode structure for generating an electric field (E) along a longitudinal axis of the positron trap (10), so as to aid axial extraction of thermalized positrons from the positron trap.

7. The apparatus of claim 6, wherein the electrode structure comprises a grid (23) arranged at an axial distance from the moderator (22).

8. The apparatus of claim 7, comprising a frame (24),

wherein the moderator (22) is suspended in said frame (24) by at least two foil-carrying wires (25) extending in parallel across the frame (24), and

wherein the grid (23) is suspended in said frame (24) by at least two grid-carrying wires (26) extending in parallel across the frame (24).

9. The apparatus of claim 6, wherein the electrode structure (70) comprises a plurality of concentric annular electrodes (71) arranged sequentially along the longitudinal axis.

10. An apparatus for moderation of positrons, the apparatus comprising:

a positron trap (10),

a moderator (22) arranged in the positron trap in a manner that positrons repeatedly pass through the moderator (22) when they are confined in the positron trap (10); and

an electrode structure (70) for generating an electric field (E) along a longitudinal axis of the positron trap (10) so as to aid axial extraction of positrons from the positron trap after they have been moderated inside the positron trap (10),

characterized in that the electrode structure (70) comprises a plurality of concentric annular electrodes (71) arranged sequentially along the longitudinal axis.

11. The apparatus of any one of the preceding claims, wherein the positron trap (10) is a cyclotron trap, the cyclotron trap defining a trap center (C) and a central longitudinal axis, the cyclotron trap comprising a magnetic field source (11, 12) configured to create a magnetic field (B) that has cylindrical symmetry about the longitudinal axis, a local minimum (Bmin) at the trap center and two equal maxima (Bmax) on the longitudinal axis at equal distances from the trap center (C).

12. The apparatus of any one of the preceding claims, comprising at least one guiding coil (60) that extends away from the positron trap (10) along the longitudinal axis, the guiding coil (60) being configured to guide thermalized positrons into a region outside the positron trap (10) after the positrons have been extracted from the positron trap (10).

13. A method of moderating positrons, the method comprising:

creating positrons inside a positron trap (10);

confining the positrons in the positron trap (10); and

slowing down the positrons by repeatedly passing the positrons through a moderator (22);

characterized in that the positrons are created in a positron source in the form of a foil or at least one mesh inside the positron trap, the positron source being either identical with the moderator (22) or including a separate source foil (21) or source mesh arranged inside the positron trap.

14. The method of claim 13, comprising bombarding the positron source inside the positron trap (10) with a particle beam (31), thereby creating at least one positron-emitting radioactive isotope or positron-electron pairs *in situ*.

15. The method of claim 13 or 14, further comprising:

implanting positrons into the moderator (22) after they have been slowed down;

allowing the positrons to thermalize in the moderator (22); and

extracting thermalized positrons from the positron trap (10) after they have been re-emitted from the moderator (22) along a longitudinal axis of the positron trap (10) with the aid of an electric field (E).

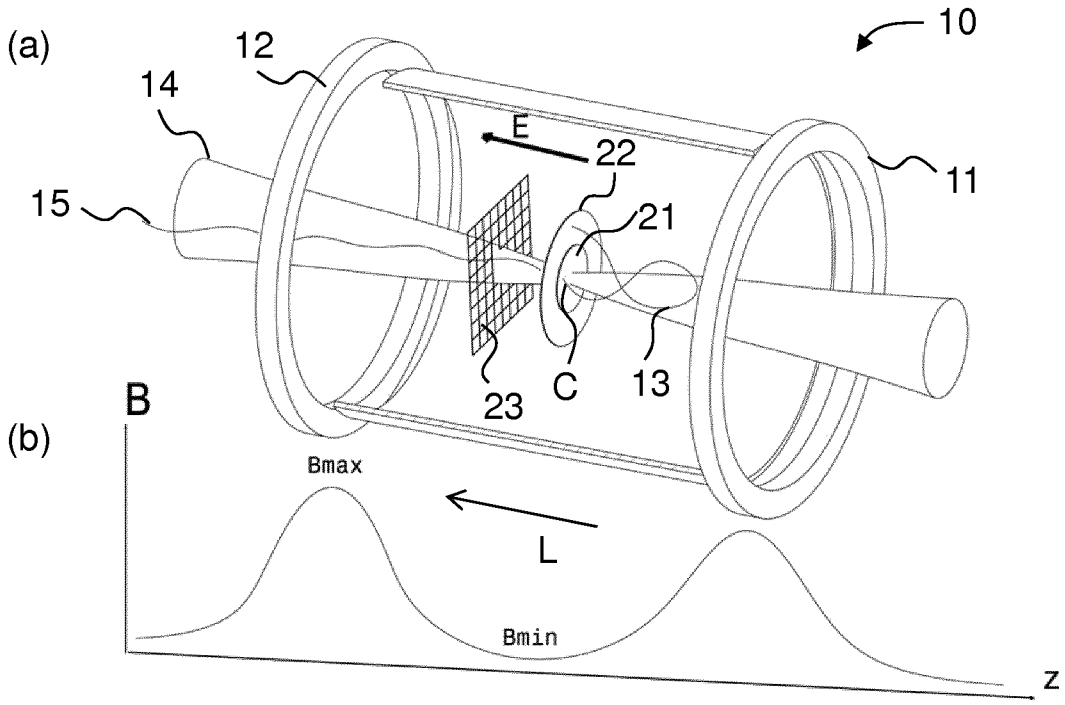
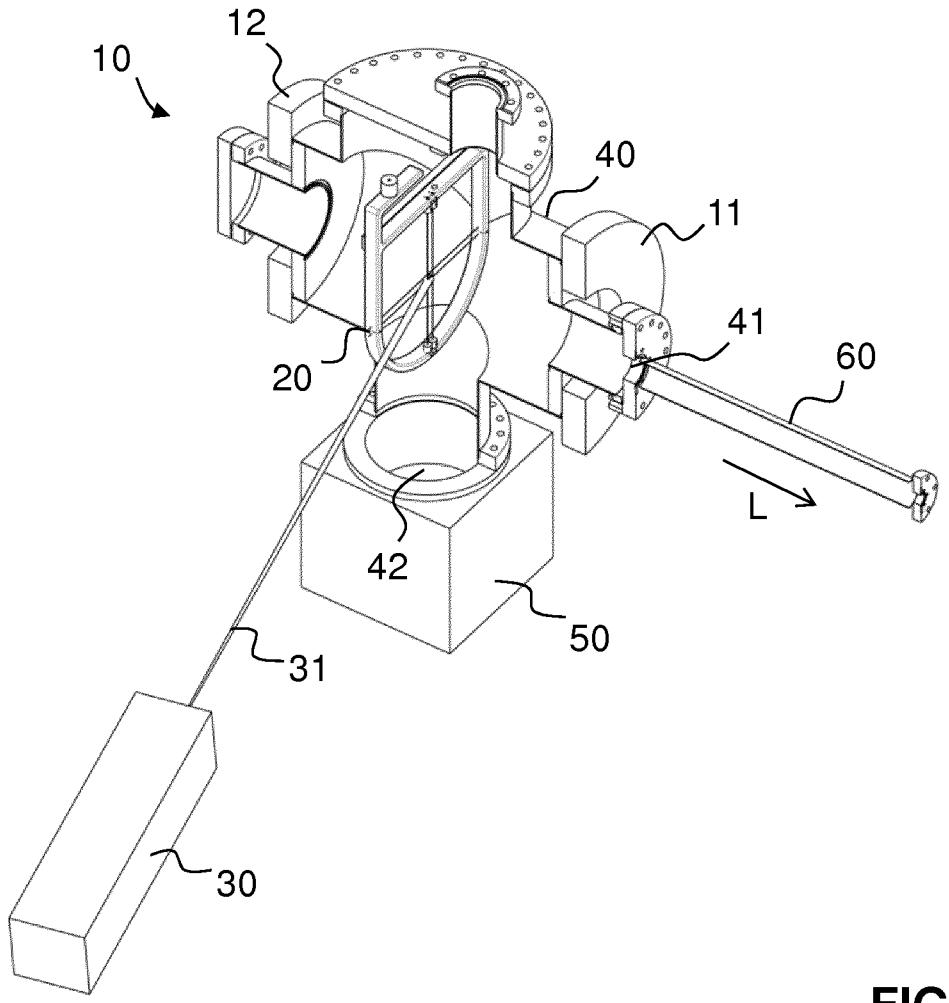

(a)
10
12
14
15
E
22
11
21
23
C
13
(b)
B
Bmax
L
Bmin
z

FIG. 1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10
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11
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31
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FIG. 2

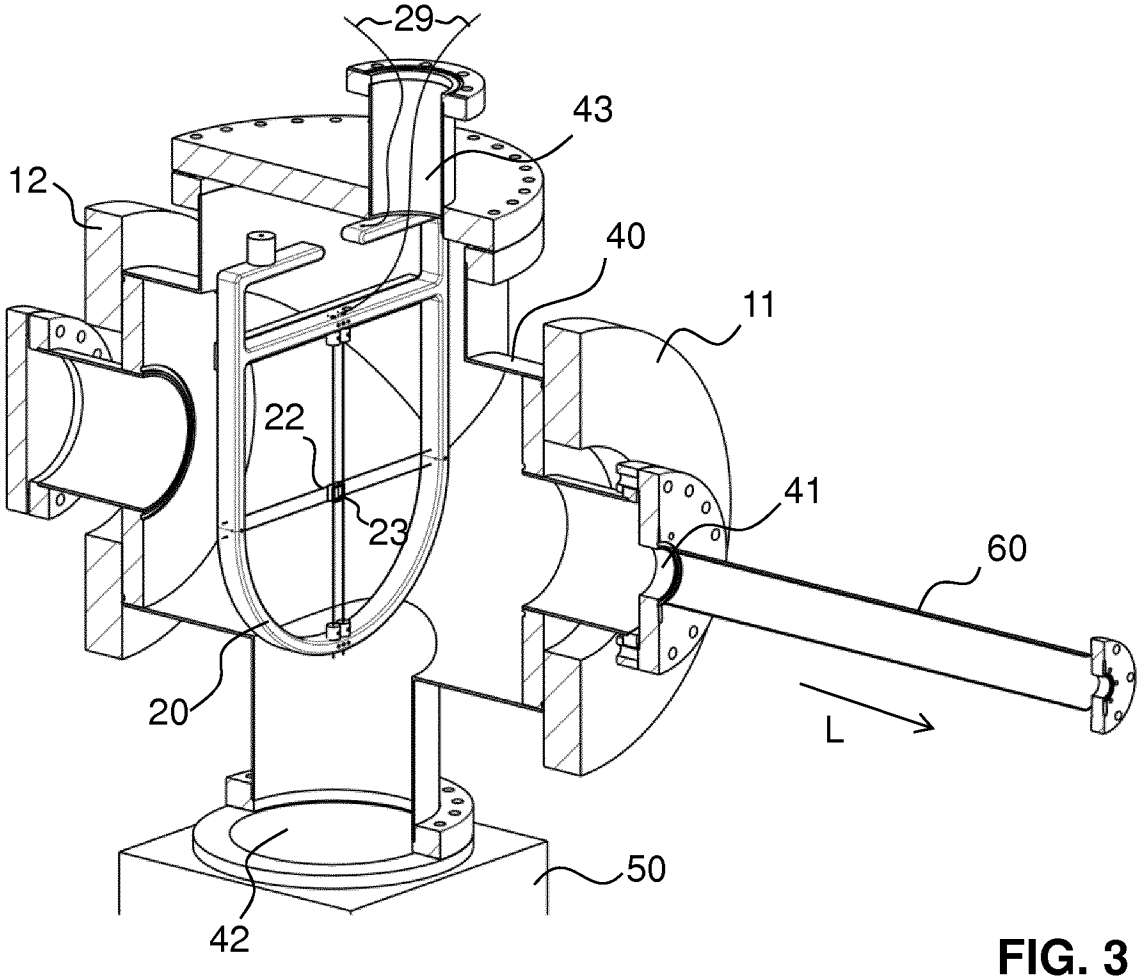


FIG. 3

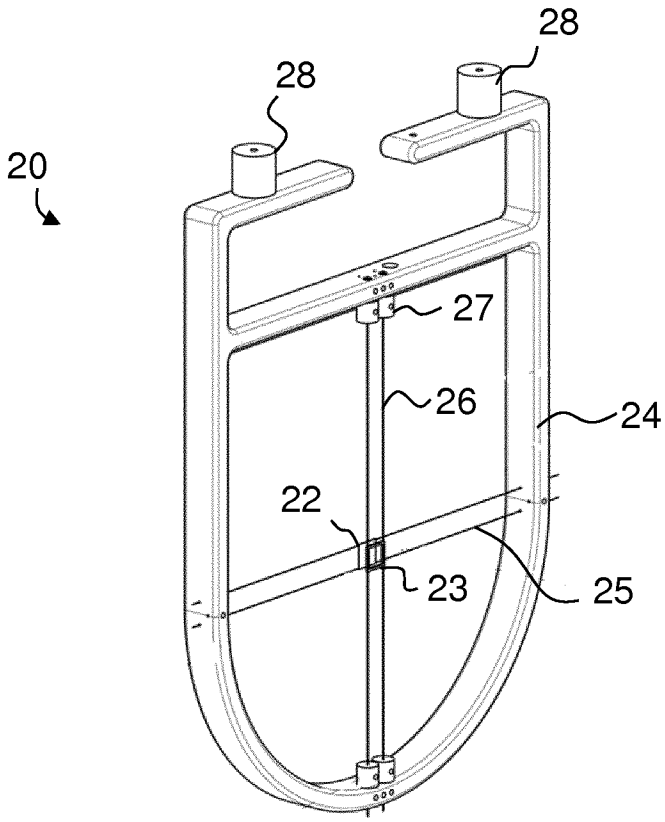
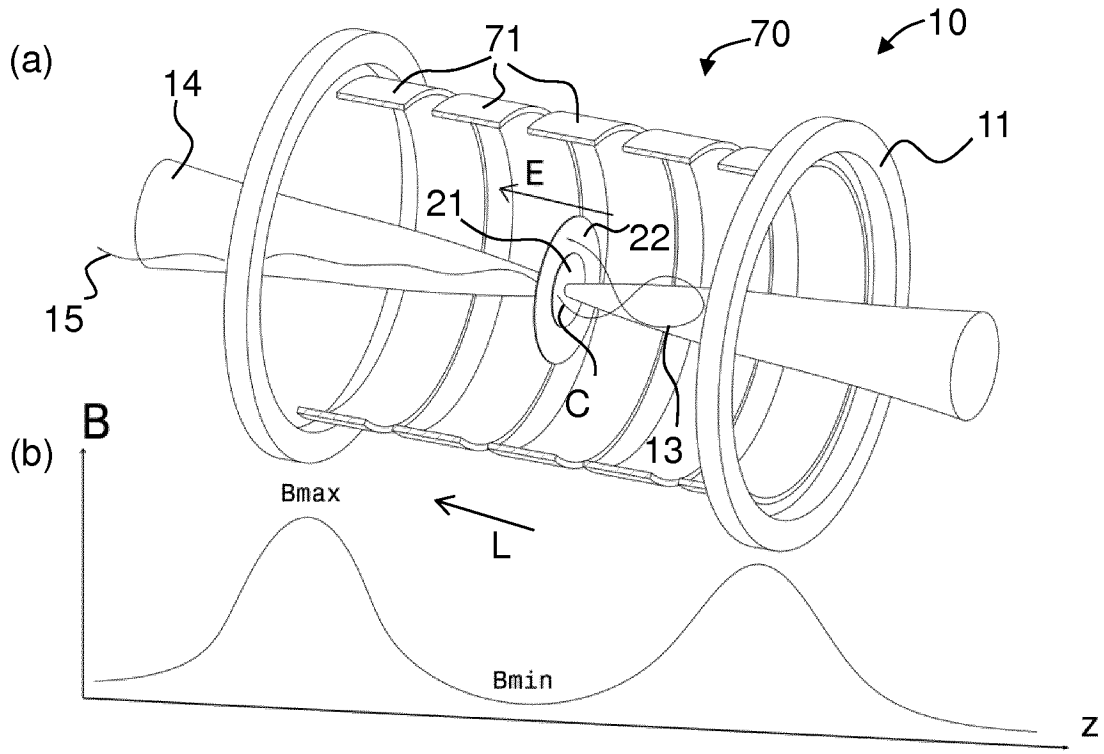


FIG. 4


(a)
71
70
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14
11
E
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22
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C
13
(b)
B
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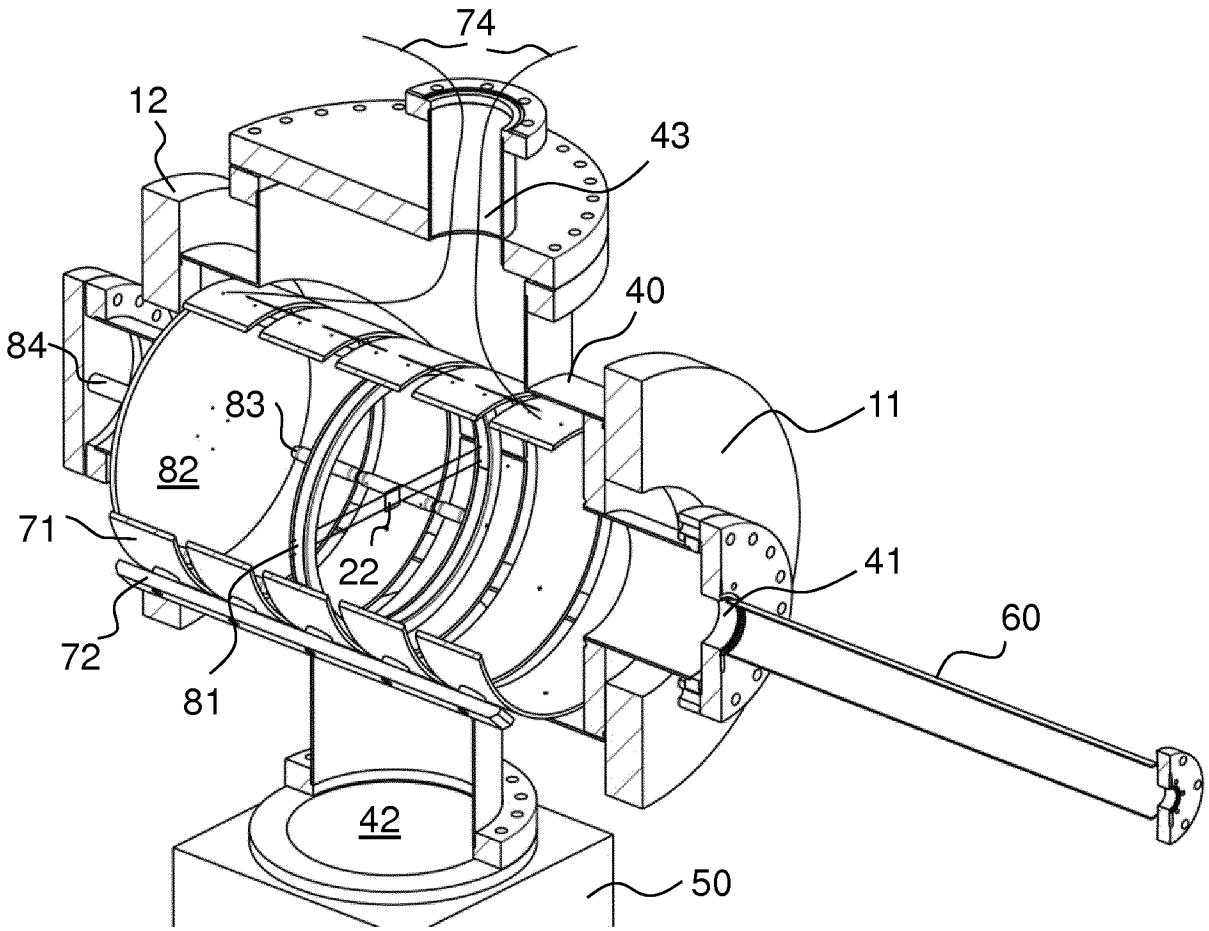
L
Bmin
z

FIG. 5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83
11
82
71
22
41
60
72
81
42
50

FIG. 6

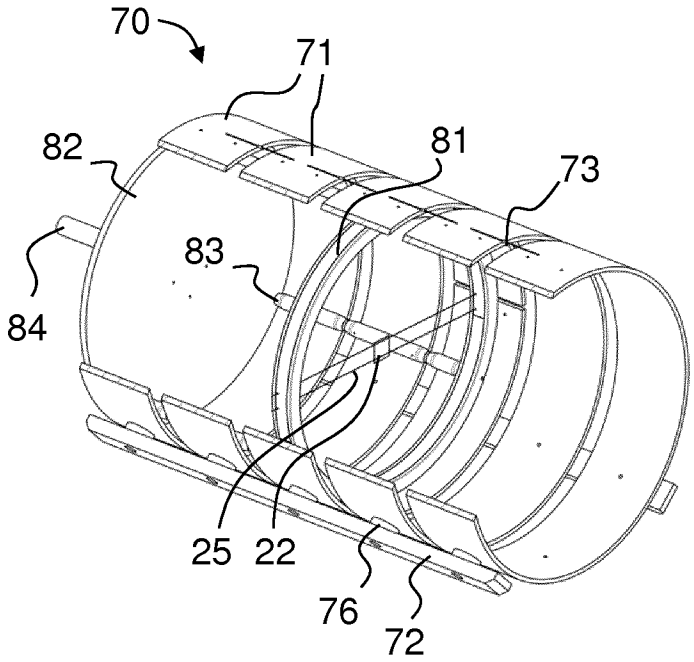

FIG. 7

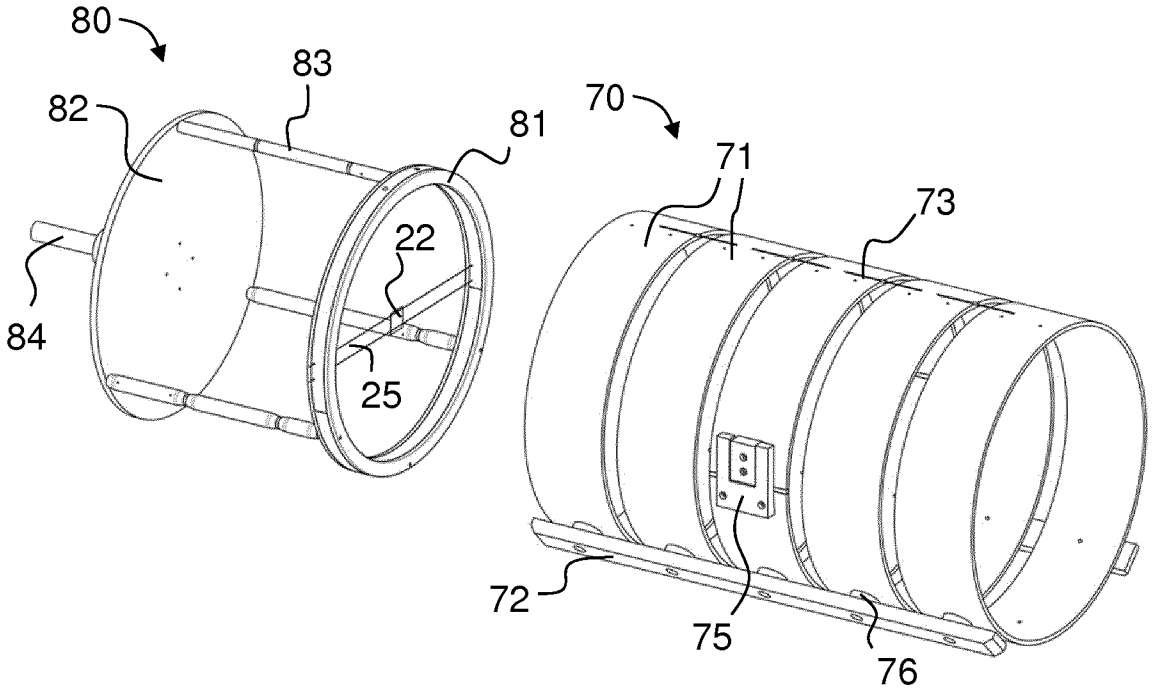

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/075355

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01J37/06
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01J G21K

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

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

EPO-Internal, WPI Data, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009/134344 A1 (AKERS DOUGLAS WILLIAM [US]) 28 May 2009 (2009-05-28)	1-3, 5-10, 13-15
Y	abstract; figures paragraphs [0005], [0018] - [0064]	1-3, 5-10, 13-15
A		11,12
Y	W. B. WAEBER ET AL: "Development of a high intensity low energy positron beam", AIP CONFERENCE PROCEEDINGS, vol. 303, 1 January 1994 (1994-01-01), pages 365-381, XP055365037, NEW YORK, US ISSN: 0094-243X, DOI: 10.1063/1.45517 cited in the application the whole document	1-15

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 December 2017	20/12/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Schmidt-Kärst, S

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Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	M. SHI ET AL: "Premoderation of positrons - Experiments on positron trapping and slowing-down", NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A: ACCELERATORS, SPECTROMETERS, DETECTORS, AND ASSOCIATED EQUIPMENT, vol. 349, no. 1, 1 September 1994 (1994-09-01), pages 8-14, XP055365538, NL ISSN: 0168-9002, DOI: 10.1016/0168-9002(94)90601-7 cited in the application the whole document	1-15
Y	DOYAMA M ET AL: "Imaging plates used as positron microscopy - Effect of positrons and gamma-rays", NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION B: BEAM INTERACTIONS WITH MATERIALS AND ATOMS, ELSEVIER BV, NL, vol. 171, no. 1-2, 1 August 2000 (2000-08-01), pages 194-198, XP004214647, ISSN: 0168-583X, DOI: 10.1016/S0168-583X(00)00109-9 page 195	1-3,5-15
Y	SANTOS A C F ED - BRAUCHER RÉGIS ET AL: "New positron sources using a 1.7MV tandem and a RDS-112 cyclotron accelerators", NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION B: BEAM INTERACTIONS WITH MATERIALS AND ATOMS, vol. 261, no. 1, 28 March 2007 (2007-03-28), pages 900-903, XP029159288, ISSN: 0168-583X, DOI: 10.1016/J.NIMB.2007.03.050 page 900 page 902 - page 903; figure 4	1-15
Y	T MURANAKA ET AL: "Development of mini linac-based positron source and an efficient positronium convertor for positively charged antihydrogen production", JOURNAL OF PHYSICS: CONFERENCE SERIES, vol. 225, 1 April 2010 (2010-04-01), page 012039, XP055365359, DOI: 10.1088/1742-6596/225/1/012039 the whole document	1,4-15

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2002/030160 A1 (GREAVES RODERICK G [US]) 14 March 2002 (2002-03-14) paragraphs [0038] - [0043]; figure 1	6,9,10
A	GEROLA D ET AL: "High efficiency positron moderation A feasibility study of the slow beam confinement extraction", NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A: ACCELERATORS, SPECTROMETERS, DETECTORS, AND ASSOCIATED EQUIPMENT, ELSEVIER BV * NORTH-HOLLAND, NL, vol. A364, no. 1, 21 September 1995 (1995-09-21), pages 33-43, XP004009722, ISSN: 0168-9002, DOI: 10.1016/0168-9002(95)00392-4 cited in the application the whole document	1-15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2017/075355

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☒ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-15

Apparatus for moderation of positrons comprising
- a positron trap; and
- a moderator arranged in the positron trap in a manner that positrons repeatedly pass through the moderator when they are confined in the positron trap.

1.1. claims: 1-9, 11-15

Apparatus for moderation of positrons comprising
- a positron trap; and
- a moderator arranged in the positron trap in a manner that positrons repeatedly pass through the moderator when they are confined in the positron trap,
wherein the positron source is in the form of a foil or at least one mesh.

1.2. claim: 10

Apparatus for moderation of positrons comprising
- a positron trap; and
- a moderator arranged in the positron trap in a manner that positrons repeatedly pass through the moderator when they are confined in the positron trap,
further comprising an electrode structure for generating an electric field along a longitudinal axis of the positron trap so as to aid axial extraction of positrons from the positron trap after they have been moderated inside the positron trap, said electrode structure comprising a plurality of concentric annular electrodes arranged sequentially along the longitudinal axis.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2017/075355

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2009134344 A1	28-05-2009	NONE	
US 2002030160 A1	14-03-2002	NONE	