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(54) **MULTIPLE ENERGY ELECTRON ACCELERATOR**

(57) Electron accelerator having a resonant cavity (10), an electron source (20) for injecting a beam of electrons (40) into the cavity, an RF source (50) adapted to generate an electric field (E) into the cavity for accelerating the electrons (40) a plurality of times inside the cavity up to a main accelerator output (42a), and beam deflectors (30) arranged outside the cavity and configured to redirect outgoing electrons back into the cavity. At least one of the beam deflectors (30) comprises a plurality of deflection magnets including a kicker magnet (80) configured to deviate the electron beam from a nominal trajectory and towards an intermediate accelerator output (41 a).

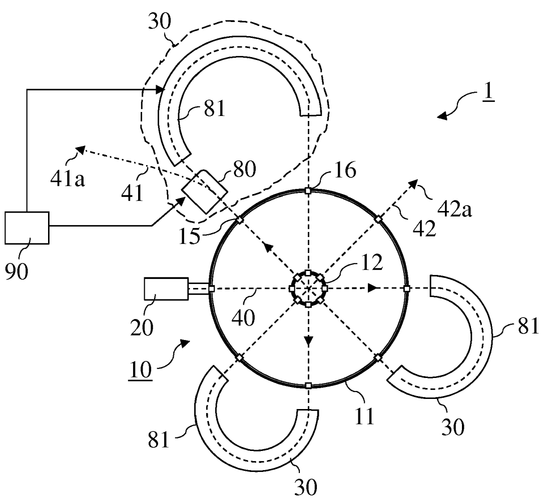

Fig. 2

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Description

Field of the invention

[0001] The invention relates to an electron accelerator having a resonant cavity wherein the electrons are accelerated a plurality of times and according to successive passages through the cavity, increasing the energy of the electrons after each passage. A typical example of such an accelerator is a Rhodotron® , which is an electron accelerator having a single coaxial cavity wherein the electrons are first injected and then accelerated transversally a plurality of times according to a trajectory having the overall shape of a flower ("Rhodos" means flower in Greek).

[0002] The invention also relates to a material detection system comprising such an electron accelerator and to a material irradiation system comprising such an electron accelerator.

Description of prior art

[0003] Such accelerators are known for example from US patent publication number US-5107221, describing a Rhodotron® which typically includes the following subsystems:

- a resonant cavity presenting two coaxial cylindrical conductors which are shorted at their ends and which present a plurality of circumferential holes at the level of their median transversal plane so as to let electrons pass through,
- an electron source which is adapted generate and to inject a beam of electrons into the cavity following a radial direction in the median transversal plane of the cavity,
- an RF source coupled to the cavity and adapted to generate a transverse electric field into the cavity for accelerating the electrons of the electron beam a plurality of times into the median transversal plane and according to successive trajectories following angularly shifted diameters of the cavity,
- deflection magnets configured for receiving the electron beam after it emerges out of the cavity and for redirecting the electron beam in the median transversal plane towards the centre of the cavity, and
- an electron beam output port.

[0004] Such accelerator may for example operate under a continuous wave (CW) mode, which means that, when in operation, RF power from the RF source is continuously applied to the cavity and the electron source injects electrons into the cavity by bunches at the same frequency as the RF frequency, which is typically about 100 MHz to 200 MHz for current commercial Rhodotrons®. Hence, a "continuous wave" of accelerated electrons is delivered at the electron beam output port of the accelerator.

[0005] Rhodotrons®, such as those which have been commercialized by the applicant for instance, typically deliver beam energies up to 10 MeV, with maximum beam power ranging from 25 KW to 700 KW.

[0006] Combined with peripheral equipment, such as beam guiding systems, beam focussing systems, beam scanning systems, and detectors for instance, these kind of accelerators are currently used for detection and security purposes for instance, such as for the detection of forbidden or hazardous substances and goods (such as weapons, explosives, drugs , etc.) which are hidden in containers.

[0007] For these and other applications in particular, it is desired to provide electron beams at two or more different energies, because this enables to better discriminate content materials having different atomic numbers.

[0008] International patent publication number WO03043388 discloses for example a Rhodotron® which is adapted to deliver multiple electron beams at respectively different energies, such as 7 MeV and 10 MeV for example.

[0009] However, since this accelerator has only a single electron source, it is not capable of delivering these two beams simultaneously but rather one after the other. Concretely, with this known accelerator, the 10 MeV beam is output at a first output port for as long as all deflection magnets are energized, so that the electrons are accelerated a maximum number of times through the cavity, whereas the 7 MeV beam is output at a second output port after turning off downstream deflection magnets and for as long as these downstream deflection magnets are kept off, so that the electrons are accelerated less than the maximum number of times through the cavity.

[0010] Given the current and future needs of applications using such accelerators , such as the requirements on detection speed and quality for security applications for instance, the switching time between the two energies is however too slow with this conventional technology. This switching time is also too slow for other applications such as for the irradiation of materials or substances with the electron beams.

Summary of the invention

[0011] It is an object of the invention to provide a an electron accelerator of the recirculating type which is capable of delivering at least two electron beams at respectively at least two different energies and in a faster time-interlaced fashion than what known accelerators of this type are capable to do.

[0012] The invention is defined by the independent claims. The dependent claims define advantageous embodiments.

[0013] According to the invention, there is provided an electron accelerator comprising :

- a resonant cavity having an outer conductor and an inner conductor,

- an electron source adapted to generate and to inject a beam of electrons transversally into the cavity,
- an RF source coupled to the cavity and adapted to generate a resonant transverse electric field into the cavity between the outer conductor and the inner conductor, so as to accelerate the electrons of the electron beam a plurality of times into the cavity and according to successive and different transversal trajectories until it reaches a main accelerator output,
- beam deflectors arranged outside the cavity, each configured to receive the electron beam from an exit port of the cavity and to redirect the electron beam according to a nominal path to an entry port of the cavity,

wherein at least one of the beam deflectors comprises a plurality of beam deflection magnets arranged in sequence, and wherein said plurality of deflection magnets comprises a kicker magnet configured to deviate the electron beam away from said nominal path towards an intermediate accelerator output.

[0014] Thanks to the kicker magnet - which can be made much smaller and much faster than the other beam deflection magnets of the beam deflector - it becomes indeed possible and at a faster pace to :

- deviate, for a first period of time, the electron beam from its nominal path before it has made further or all acceleration passes through the cavity, thereby delivering, to the intermediate accelerator output, a first electron beam at a first energy during the first period of time,
  and to
- not deviate, for a second period of time, the electron beam from its nominal path before it has made further or all passes through the cavity, thereby delivering, to a further intermediate accelerator output or to the main accelerator output, a second electron beam at a second energy during the second period of time, different from said first period of time, said second energy being higher than the first energy.

[0015] An electron accelerator according to the invention is therefore capable of delivering at least two electron beams at respectively at least two different energies in a fast time-interlaced fashion.

[0016] Preferably, the electron accelerator further comprises a control unit configured to repeatedly switch the kicker magnet ON and OFF. More preferably, the control unit is configured to repeatedly switch the kicker magnet ON and OFF with a minimum time between two successive ON states which is less than 1/10 sec, preferably less than 1/100 sec, more preferably less than 2/1000 sec.

[0017] Preferably, the kicker magnet is configured to provide - when energized - a beam bending angle smaller than 90°, preferably a beam bending angle comprised between 1 °and 20°, more preferably a beam bending angle comprised between 3° and 15°. With such a small bending angle, the kicker magnet can be made small and can have fast switching capabilities.

[0018] Preferably:

- the outer conductor and the inner conductor are coaxial cylindrical conductors of axis A, both cylindrical conductors being shorted at their distal ends with respectively a top conductive closure and a bottom conductive closure (14),
- the electron source is adapted to inject the beam of electrons into the cavity following a radial direction in a median transversal plane of the cavity,
- the RF source is adapted to generate the transverse electric field into said cavity so as to accelerate the electrons of the electron beam a plurality of times into the median transversal plane and according to successive trajectories following angularly shifted diameters of the outer cylindrical conductor, and
- the nominal path is in the median transversal plane.

[0019] Such kind of accelerator, sometimes called a Rhodotron®, is particularly well suited to achieve the aforementioned object of the invention.

[0020] More preferably, the kicker magnet is configured to deviate the electron beam away from said nominal path and towards the intermediate accelerator output while said kicker magnet is switched ON by the control unit.

[0021] Such a configuration requires indeed the least modifications to the design of a conventional accelerator. One can for instance place the kicker magnet upstream or downstream of a conventional beam deflector without too many changes to the conventional beam deflector.

[0022] Even more preferably, the kicker magnet is the first deflection magnet in the sequence of deflection magnets. With such a configuration, the required beam deflection angle of the kicker magnet can be made smaller than with other configurations.

Short description of the drawings

[0023] These and further aspects of the invention will be explained in greater detail by way of example and with reference to the accompanying drawings in which:

Fig.1	schematically shows an axial cross section of an electron accelerator according to the invention;
Fig.2	schematically shows a transversal cross section of the electron accelerator of Fig.1, according to a first embodiment;
Fig.2a	schematically shows a transversal cross section of the electron accelerator of Fig.1, according to a preferred first embodiment;
Fig.3	schematically shows a transversal cross section of the electron accelerator of Fig.1, accord-

ing to a second embodiment;

Fig.4 schematically shows a transversal cross section of the electron accelerator of Fig.1, according to a third embodiment;

Fig.5a shows exemplary time diagrams for various beam and magnet currents in case of the accelerators of Figs. 2, 2a, 3 and 4 when these accelerators operate in continuous wave mode.

Fig.5b shows exemplary time diagrams for various beam and magnet currents in case of the accelerators of Figs. 2, 2a, 3 and 4 when these accelerators operate in pulsed mode.

Fig.6 schematically shows a transversal cross section of the electron accelerator of Fig.1, according to a fourth embodiment;

Fig.7 schematically shows a transversal cross section of the electron accelerator of Fig.1, according to a fifth embodiment;

Fig.8a shows exemplary time diagrams for various beam and magnet currents in case of the accelerators of Figs. 6 and 7 when these accelerators operate in continuous wave mode.

Fig.8b shows exemplary time diagrams for various beam and magnet currents in case of the accelerators of Figs. 6 and 7 when these accelerators operate in pulsed mode.

Fig.9 schematically shows a part of a material detection system according to the invention.

Fig.10 schematically shows a part of a material irradiation system according to the invention.

[0024] The figures are not drawn to scale. Generally, similar or identical components are denoted by the same reference numerals in the figures.

Detailed description of preferred embodiments of the invention

[0025] Fig.1 schematically shows an axial cross section of an electron accelerator (1) according to the invention and comprising :

- a resonant cavity (10) having a cylindrical outer conductor (11) and a coaxial cylindrical inner conductor (12) of axis A, both cylindrical conductors being shorted at their distal ends with respectively a top conductive closure (13) and a bottom conductive closure (14),
- an electron source (20) adapted to generate and to inject a beam of electrons (40) into the resonant cavity (10) following a radial direction in a median transversal plane (MP) of the resonant cavity (10),
- an RF source (50) coupled to the resonant cavity (10) and adapted to generate a transverse electric field (E) into the resonant cavity (10) between the outer conductor (11) and the inner conductor (12), so as to accelerate the electrons of the electron beam (40) a plurality of times into the median transversal plane (MP), into the cavity (10) and according to successive trajectories following angularly shifted diameters of the outer cylindrical conductor (11), until they reach an accelerator output (41 a, 42a),
- beam deflectors (30) arranged outside the resonant cavity (10), each configured to receive the electron beam from an exit port (15) of the cavity (10) and to redirect the electron beam according to a nominal path to an entry port (16) of the resonant cavity (10), said nominal path being in the median transversal plane (MP).

[0026] Such an electron accelerator (1) is sometimes called a "Rhodotron®" and is basically well known in the art. Other types of accelerators, such as recirculating Linacs for example, may also be used.

[0027] Attention will now be drawn more specifically to the beam deflectors (30) and to their control unit (90).

[0028] In an accelerator according to the invention, at least one of the beam deflectors (30) comprises a plurality of beam deflection magnets arranged in sequence. Said plurality of beam deflection magnets comprises a kicker magnet (80) configured to deviate the electron beam (40) away from said nominal path towards an intermediate accelerator output (41 a) for use by an application such as those described hereafter for example (material detection or material irradiation).

[0029] The electron accelerator (1) preferably further comprises a control unit (90) configured to repeatedly switch said kicker magnet (80) ON and OFF. Preferably, the control unit (90) is configured to repeatedly switch said kicker magnet (80) ON and OFF with a minimum time between two successive ON states which is less than 1/10 sec, preferably less than 1/100 sec, more preferably less than 2/1000 sec.

[0030] Such control unit (90) may for example comprise a pulse generator and a current amplifier, the current amplifier being steered by the pulse generator and delivering a pulsed excitation current to the kicker magnet (current I_k, as can be seen on Figs. 5a, 5b, 8a, and 8b). The control unit (90) may alternatively be a programmable current source. An exemplary programmable current source is the GMW-231 HC bipolar current amplifier commercialized by GMW Associates, which allows for USB or direct analogue programming of the current output.

[0031] Fig.2 schematically shows a transversal cross section of the electron accelerator (1) of Fig.1, and according to a first embodiment.

[0032] In this exemplary first embodiment, the outer cylindrical conductor (11) of the cavity (10) comprises four beam entry ports and four beam exit ports, as well as thee beam deflectors (30) arranged outside the cavity (10), each beam deflector (30) being configured to receive the electron beam from an exit port (15) of the cavity (10) and to redirect the electron beam according to a nominal path towards an entry port (16) of the cavity (10), as shown on Fig.2. The nominal path of the electron beam

(40) is indicated by a dashed line starting from the electron source (20) and ending at the main accelerator output (42a). Obviously, the accelerator may comprise more than three beam deflectors (30) or less than three beam deflectors (30), and, accordingly, more or less than four entry and exit ports in the outer conductor (11).

[0033] As shown on Fig.2 and encircled by a long-dashed line, one of the beam deflectors (30) comprises two beam deflection magnets arranged in sequence: a kicker magnet (80), followed by a main magnet (81). The kicker magnet (80) and the main magnet (81) are preferably electromagnets. The kicker electromagnet (80) may use either a standard iron-laminated yoke or a ferrite-based yoke, the latter being known to be more suitable at higher switching frequencies because it generates less Eddy currents.

[0034] The kicker magnet (80) is preferably placed in the straight path of the electron beam (40) after leaving the exit port (15) of the cavity (10) and is arranged and designed in such a way that, when it is switched OFF by the control unit (90), the electron beam (40) will simply pass through it without deviation and will continue its straight trajectory towards the main magnet (81) which will then redirect the electron beam (40) towards the corresponding entry port (16) of the cavity (10) for further acceleration into the cavity. Hence, for as long as the kicker magnet (80) remains switched OFF, the electron beam (40) will continue its trajectory towards the main accelerator output (42a) and therefore make a total of four acceleration passes through the cavity (10) in the present example. For as long as the kicker magnet (80) remains switched OFF, the main accelerator output (42a) will therefore deliver a second electron beam (42) at an energy corresponding to these four successive acceleration passes.

[0035] The kicker magnet (80) is furthermore arranged and designed in such a way that, when it is switched ON by the control unit (90), it will generate a magnetic field which will deviate the electron beam away from said nominal trajectory towards an intermediate accelerator output (41 a), as shown by a dashed-dotted line on Fig.2. Hence, for as long as the kicker magnet (80) remains switched ON, the electron beam will make a total of only two acceleration passes through the cavity (10) in the present example. For as long as the kicker magnet (80) remains switched ON, the intermediate accelerator output (41 a) will therefore deliver a first electron beam (41) at an energy corresponding to these two successive acceleration passes.

[0036] This accelerator is therefore capable of delivering two electron beams at respectively two accelerator outputs (intermediate output and main output) and at respectively two different energies, in a fast time-interlaced fashion.

[0037] In the example of Fig.1 and Fig.2, the main magnet (81), when energized, provides a total beam bending angle of 225°, whereas the kicker magnet (80), when energized, provides a beam bending angle much smaller than 225°. In all embodiments of the present invention, the kicker magnet (80) is preferably configured to provide, when energized, a beam bending angle smaller than 90°, preferably a beam bending angle comprised between 1 °and 20°, more preferably a beam bending angle comprised between 3°and 15°.

[0038] It is to be noted that the main magnet (81) may be in one part, as shown on Fig.2, or in several successive parts, as will be described in relation to Fig.4 for example.

[0039] Fig.2a schematically shows a transversal cross section of the electron accelerator of Fig.1, according to a preferred first embodiment. It is similar to the embodiment shown on Fig.2, except that, in this preferred first embodiment, the kicker magnet (80) and the main magnet (81) are arranged and configured in such a way that the first electron beam (41), i.e. the electron beam leaving the kicker magnet (80) when the kicker magnet (80) is ON, falls under the influence of the magnetic field generated by the main magnet (81). In other words, the kicker magnet (80) and the main magnet (81) are arranged and configured in such a way that the first electron beam (41), passes between the poles of the main magnet (81) for at least a part of its trajectory for as long as the kicker magnet (80) is ON. To achieve this, and as illustrated on Fig.2a, one may for example make the poles of the main magnet wider than they are in the case of Fig.2, and/or by placing the main magnet (81) closer to the kicker magnet (80).

[0040] Hence, the first electron beam (41) will be bent by said magnetic field of the main magnet after said first electron beam (41) has left the excited kicker magnet. Such a preferred configuration allows to redirect the first electron beam (41) to a direction which is different than the direction it had when leaving the kicker magnet (80), yet without requiring extra beam bending magnets. The main magnet therefore has a double function in this preferred first embodiment: it bends the electron beam back to the entry port (16) of the cavity for further acceleration into the cavity while the kicker magnet is OFF, and it deviates the electron beam to a different direction than the direction it had when leaving the kicker magnet while the kicker magnet is ON.

[0041] Fig.3 schematically shows a transversal cross section of the electron accelerator (1) of Fig.1, according to a second embodiment. This second embodiment is similar to the first embodiment, except that the kicker magnet (80) is in this case placed after (downstream of) the main magnet (81) instead of before (upstream of) the main magnet.

[0042] Fig.4 schematically shows a transversal cross section of the electron accelerator (1) of Fig.1, according to a third embodiment. This third embodiment is similar to the first embodiment, except that the main magnet is divided into two parts (81 a, 81 b) and except that the kicker magnet (80) is in this case placed in the beam path between these two parts of the main magnet. In this example, the two parts (81 a, 81 b) of the main magnet are arranged symmetrically and each part provides a total beam bending angle of 112,5 °, but many other configurations in two or more parts of the main magnet may of course be used.

[0043] In the case of this third embodiment, and by analogy with the configuration illustrated in Fig.2a, the kicker magnet (80) and the second part (81 b) of the main magnet (81) are preferably arranged and configured in such a way that the first electron beam (41), i.e. the electron beam leaving the kicker magnet (80) when the kicker magnet (80) is ON, falls under the influence of the magnetic field generated by the said second part (81 b) of the main magnet (81). In other words, the kicker magnet (80) and the second part (81 b) of the main magnet (81) are arranged and configured in such a way that the first electron beam (41), passes between the poles of the second part (81 b) of the main magnet (81) for at least a part of its trajectory for as long as the kicker magnet (80) is ON.

[0044] To achieve this, one may for example make the poles of the second part (81 b) of the main magnet (81) wider than they are in the case of Fig.4, and/or by placing the main magnet (81) closer to the second part (81 b) of the main magnet (81). Hence, the first electron beam (41) will be bent by said magnetic field of the second part (81 b) of the main magnet (81) after said first electron beam (41) has left the excited kicker magnet.

[0045] Such a preferred configuration allows to redirect the first electron beam (41) to a direction which is different than the direction it had when leaving the kicker magnet (80), yet without requiring extra beam bending magnets. The second part (81 b) of the main magnet (81) therefore has a double function in this preferred third embodiment: it bends the electron beam back to the entry port (16) of the cavity for further acceleration into the cavity while the kicker magnet is OFF, and it deviates the electron beam to a different direction than the direction it had when leaving the kicker magnet while the kicker magnet is ON.

[0046] Fig.5a shows exemplary time diagrams for various beam and magnet currents in case of the accelerators of Figs. 2, 2a, 3 and 4, when these accelerators operate in continuous wave (CW) mode.

[0047] The first time diagram shows the excitation current (I_k) of the kicker magnet (80) over time. This excitation current is provided by the control unit (90). In the present example, the excitation current is periodic and has a frequency f_k, but it may as well be aperiodic.

[0048] The second time diagram shows the electron beam current (I_0) at an output of the electron source (20). For clarity reasons, this diagram does not show a possible microstructure in this beam current. With actual commercial Rhodotrons®, the electron source (20) injects indeed electrons into the cavity (10) by bunches at the same frequency as the RF frequency, which is typically about 100 MHz to 200 MHz.

[0049] The third time diagram shows the electron beam current (I_1) at the intermediate accelerator output (41 a).

[0050] The fourth time diagram shows the electron beam current (I_2) at the main accelerator output (42a).

[0051] Since the excitation current (I_k) of the kicker magnet (80) is periodic in the present example, the electron beam current at the intermediate accelerator output (I_1) and at the main accelerator output (I_2) will also be periodic and at the same frequency f_k.

[0052] Obviously, the duty cycle of the excitation current (I_k) of the kicker magnet (80) will determine the pulse duration at the intermediate accelerator output (TP1) and at the main accelerator output (TP2).

[0053] Fig.5b shows exemplary time diagrams for various beam and magnet currents in case of the accelerators of Figs. 2, 2a, 3 and 4, when these accelerators operate in pulsed-mode. A pulsed-mode accelerator has for example been described in patent publication number WO2014184306A1, which is incorporated herein by reference.

[0054] The first time diagram shows the excitation current (I_k) of the kicker magnet (80) over time. This excitation current is provided by the control unit (90). In the present example, the excitation current is periodic and has a frequency f_k, but it may as well be aperiodic.

[0055] The second time diagram shows the electron beam current (I_0) at an output of the electron source (20). Again for clarity reasons, this diagram does not show a possible microstructure in this beam current. In the present example, the electron beam current is periodic and has a frequency f_0 with a pulse duration TP_0, but it may as well be aperiodic.

[0056] The third time diagram shows the electron beam current (I_1) at the intermediate accelerator output (41 a).

[0057] The fourth time diagram shows the electron beam current (I_2) at the main accelerator output (42a).

[0058] Since the excitation current (I_k) of the kicker magnet (80) is periodic in the present example, the electron beam current at the intermediate accelerator output (I_1) and at the main accelerator output (I_2) will also be periodic and at the same frequency f_k.

[0059] Obviously, the pulse duration (TP_0) of the electron beam current (I_0) will determine the pulse duration at the intermediate accelerator output (41 a) and at the main accelerator output (42a).

[0060] Obviously, the duty cycle of the excitation current (I_k) of the kicker magnet (80) will determine the interlacing patterns of the electron beam current (I_1) at the intermediate accelerator output (41 a) and the electron beam current (I_2) at the main accelerator output (42a).

[0061] Fig.6 schematically shows a transversal cross section of the electron accelerator (1) of Fig.1, according to a fourth embodiment.

[0062] This fourth embodiment is similar to the first embodiment, except that the kicker magnet (80) is arranged and controlled differently.

[0063] The kicker magnet (80) is placed in the trajectory of the electron beam (40) leaving the exit port (15) of the cavity (10) and it is in this case arranged and designed in such a way that, when it is switched ON by the control unit (90), the electron beam will be deviated towards the main magnet (81) which will then redirect the beam towards the corresponding entry port (16) of the cavity (10) for further acceleration into the cavity. Hence, for as long as the kicker magnet (80) remains switched ON, the electron beam will continue its trajectory towards the main accelerator output (42a) and therefore make a total of four acceleration passes through the cavity (10) in the present example. The main accelerator output (42a) will therefore deliver a second electron beam (42) at an energy corresponding to these four successive acceleration passes, for as long as the kicker magnet (80) remains switched ON.

[0064] The kicker magnet (80) is furthermore arranged and designed in such a way that, when it is switched OFF by the control unit (90), the electron beam will simply pass through it without deviation and continue a straight trajectory towards the intermediate accelerator output (41 a), as shown by a dashed-dotted line on Fig.6. Hence, for as long as the kicker magnet (80) remains switched OFF, the electron beam makes a total of only two acceleration passes through the cavity (10) in the present example. The intermediate accelerator output (41 a) will therefore deliver a first electron beam (41) at an energy corresponding to these two successive acceleration passes, for as long as the kicker magnet (80) remains switched OFF.

[0065] This electron accelerator is therefore also capable of delivering two electron beams at respectively two accelerator outputs (main output and intermediate output) and at respectively two different energies, in a fast time-interlaced fashion.

[0066] In the case of this fourth embodiment, and again by analogy with the configuration illustrated in Fig.2a, the kicker magnet (80) and the main magnet (81) are preferably arranged and configured in such a way that the first electron beam (41), i.e. the electron beam leaving the kicker magnet (80) when the kicker magnet (80) is OFF, falls under the influence of the magnetic field generated by the main magnet (81), so that the first electron beam (41) will be bent by said magnetic field after said first electron beam (41) has left the unexcited kicker magnet. In other words, the kicker magnet (80) and the main magnet (81) are arranged and configured in such a way that the first electron beam (41), passes between the poles of the main magnet (81) for at least a part of its trajectory for as long as the kicker magnet (80) is OFF. To achieve this, one may for example make the poles of the main magnet wider than they are in the case of Fig.6, and/or by placing the main magnet (81) closer to the kicker magnet (80). Hence, the first electron beam (41) will be bent by said magnetic field of the main magnet after said first electron beam (41) has left the unexcited kicker magnet.

[0067] Fig.7 schematically shows a transversal cross section of the electron accelerator (1) of Fig.1, according to a fifth embodiment.

[0068] This fifth embodiment is similar to the fourth embodiment shown in Fig.6, except that the kicker magnet (80) is placed after (downstream of) the main magnet (81) in this case.

[0069] Fig.8a shows exemplary time diagrams for various beam and magnet currents in case of the accelerators of Figs. 6 and 7, when these accelerators operate in continuous wave mode. The order of the time diagrams and the symbols used are the same as in Fig. 5a.

[0070] Fig.8b shows exemplary time diagrams for various beam and magnet currents in case of the accelerators of Figs. 6 and 7, when these accelerators operate in pulsed mode. The order of the time diagrams and the symbols used are the same as in Fig. 5b.

[0071] In any embodiment of the accelerator according to the invention, the control unit (90) is preferably configured to vary the time during which the kicker magnet (80) is switched ON and/or to vary the time during which the kicker magnet (80) is switched OFF. A pulse width modulator can be used for this purpose for instance. This allows to change the duty cycle and hence the interlacing patterns at the accelerator outputs.

[0072] Furthermore, in case the control unit (90) is configured to repeatedly switch the kicker magnet (80) ON and OFF in a periodic fashion at a switching frequency, the control unit (90) is preferably adapted to vary said switching frequency.

[0073] Preferably, the RF source (50) is adapted to energize the cavity (10) at a nominal RF frequency which is higher than 50MHz and lower than 500 MHz.

[0074] An electron accelerator (1) according to the invention may be used for various purposes. It may for example be used for the detection of hidden and/or forbidden and/or hazardous substances and/or goods - such as weapons, explosives, drugs , etc - from an image formed either directly by the accelerated electrons or indirectly, for example by X-rays produced by said electrons after hitting a metal target for instance. It may also be used for the irradiation of substances by the electron beams, for example for sterilization purposes, such as food sterilization.

[0075] Fig.9 schematically shows a part of a material detection system according to the invention. It comprises an electron accelerator (1) according to the invention as described herein and which is hence adapted to produce and output in a fast time-interlaced fashion:

- a first electron beam (41) at a first energy, at an intermediate accelerator output (41 a), and
- a second electron beam (42) at a second energy, at a main accelerator output (42a),

the first energy being smaller than the second energy.

[0076] The material detection system further comprises a first RX conversion target (102) and a second RX conversion target (102) arranged respectively in the paths of the first and second electron beams coming from respectively the main and the intermediate accelerator outputs. An RX conversion target is for example a material plate which converts impinging energetic electrons into X-Rays by the so-called "Bremsstrahlung" effect.

[0077] The material detection system further comprises a first RX detector (110) and a second RX detector (120) arranged respectively in the paths of the X-rays generated respectively by the first and the second RX conversion targets (101, 102) when bombarded by respectively the first and second electron beams. When the material detection system is in operation, a container (500) - whose material content is to be inspected - may for example be moved in translation between the conversion targets and the detectors, as indicated by a plain arrow on Fig. 9. Analysis and/or imaging of the signals delivered by the RX detectors (110, 120) allows to detect materials contained into the container (500). Obviously, the material detection system may also comprise other known subsystems such as electron beam benders, scanners and/or shapers, which are not illustrated for the sake of clarity.

[0078] Fig.10 schematically shows a part of a material irradiation system according to the invention. It comprises an electron accelerator (1) according to the invention as described herein and which is hence adapted to produce and output in a fast time-interlaced fashion:

- a first electron beam (41) at a first energy, at an intermediate accelerator output (41 a), and
- a second electron beam (42) at a second energy, at a main accelerator output (42a),

the first energy being smaller than the second energy.

[0079] The first electron beam (41) is directed to a first material product to be irradiated (601), whereas the second electron beam (42) is directed to a second material product to be irradiated (602).

[0080] These material products (601, 602) may for example be food products, which will be sterilized after having been irradiated by the electron beams (41, 42). Complete irradiation of the material products may be achieved by moving these products across the electron beams or by scanning or spreading the electron beams over the products or by any other equivalent means.

[0081] Obviously, the material irradiation system may also comprise other known subsystems such as electron beam benders, scanners and/or shapers, which are not illustrated for the sake of clarity.

[0082] Many other system configurations making use of an electron accelerator (1) according to the invention may of course be envisaged. One may for example conceive a hybrid system wherein the first electron beam (41) (i.e. the low energy beam) is directed to a material product to be irradiated, as partly shown in Fig.10 for example, and wherein the second electron beam (42) (i.e. the high energy beam) is directed to an RX conversion target for material detection purposes, as partly shown in Fig.9 for example, or vice versa.

[0083] In the examples given hereinabove, only one of the beam deflectors (30) comprises a kicker magnet (80) and the accelerator comprises consequently two electron beam outputs - one intermediate output and one main output - providing two electron beams at respectively two different energies.

[0084] The invention nevertheless also provides an accelerator wherein more than one beam deflector (30) comprises a kicker magnet (80), thereby providing more than one intermediate output in addition to the main output (42a), and therefore being adapted to deliver more than two electron beams at respectively more than two different energies. In such a case, the control unit (90) is configured to repeatedly and alternatively switch these kicker magnets ON and OFF, with a minimum time between two successive ON states of a given kicker magnet which is less than 1/10 sec, preferably less than 1/100 sec, preferably less than 2/1000 sec. Preferably only one kicker magnet is switched ON at a time by the control unit (90) in case of the embodiments of Figs. 2, 3 and 4, whereas preferably only one kicker magnet is switched OFF at a time by the control unit (90) in case of the embodiments of Figs. 6 and 7.

[0085] In any embodiment of the electron accelerator (1) according to the invention, the main magnet(s) (81, 81 a, 81 b) of a beam deflector (30) is (are) preferably kept permanently switched ON while the accelerator accelerates electrons towards any of its outputs (41 a, 42a), i.e. while the kicker magnet (80) is switched ON and OFF. The main magnet(s) are those beam deflection magnets of a beam deflector (30) which are not kicker magnets (80). Switching the main magnet(s) ON and keeping them switched ON while the kicker magnet (80) is switched ON and OFF, may be performed by the control unit (90) which controls the kicker magnet(s) (80) or by any other control unit. An advantage of this preferred feature is that the magnetic field(s) of the main magnet(s) can be stabilized once, generally at the start-up of the accelerator, and remain stable for the operation time of the accelerator, so that the switching rate between the different accelerator outputs will depend mainly on the switching rate capacity of the kicker magnet(s).

[0086] The present invention has been described in terms of specific embodiments, which are illustrative of the invention and not to be construed as limiting. Reference numerals in the claims do not limit their protective scope.

[0087] Use of the verbs "to comprise", "to include", "to be composed of", or any other variant, as well as their respective conjugations, does not exclude the presence of elements other than those stated.

[0088] Use of the article "a", "an" or "the" preceding an element does not exclude the presence of a plurality of such elements.

[0089] Summarized, the invention may also be described as follows: an electron accelerator having a resonant cavity (10), an electron source (20) for injecting a beam of electrons (40) into the cavity, an RF source (50) adapted to generate an electric field (E) into the cavity for accelerating the electrons (40) a plurality of times inside the cavity according to angularly shifted trajectories up to a main accelerator output (42a), and beam deflectors (30) arranged outside the cavity and configured to redirect outgoing electrons back into the cavity for further acceleration into the cavity. At least one of the beam deflectors (30) comprises a plurality of deflection magnets arranged in sequence and including a kicker magnet (80) configured to deviate the electron beam from a nominal trajectory and towards an intermediate accelerator output (41 a). The electron accelerator preferably also comprises a control unit (90), which is configured to repeatedly switch the kicker magnet ON and OFF with a minimum time between two successive ON states which is less than 1/10 sec, preferably less than 1/100 sec, more preferably less than 2/1000 sec.

Claims

1. Electron accelerator comprising :

- a resonant cavity (10) having an outer conductor (11) and an inner conductor (12),
- an electron source (20) adapted to generate and to inject a beam of electrons (40) transversally into the cavity (10),
- an RF source (50) coupled to the cavity (10) and adapted to generate a transverse electric field (E) into the cavity between the outer conductor and the inner conductor so as to accelerate the electrons of the electron beam a plurality of times into the cavity and according to successive and different transversal trajectories until it reaches a main accelerator output (42a),
- beam deflectors (30) arranged outside the cavity (10) and each configured to receive the electron beam from an exit port (15) of the cavity and to redirect the electron beam according to a nominal path to an entry port (16) of the cavity, **characterized in that** at least one of the beam deflectors (30) comprises a plurality of beam deflection magnets arranged in sequence, said plurality of deflection magnets comprising a kicker magnet (80) configured to deviate the electron beam away from said nominal path towards an intermediate accelerator output (41 a).

2. Electron accelerator according to claim 1, **characterized in that** it further comprises a control unit (90) configured to repeatedly switch the kicker magnet (80) ON and OFF.

3. Electron accelerator according to claim 2, **characterized in that** the control unit (90) is configured to repeatedly switch the kicker magnet (80) ON and OFF with a minimum time between two successive ON states which is less than 1/10 sec, preferably less than 1/100 sec, more preferably less than 2/1000 sec.

4. Electron accelerator according to any of claims 1 to 3, **characterized in that** the kicker magnet (80) is configured to provide a beam bending angle smaller than 90°, preferably a beam bending angle comprised between 1 °and 20°, more preferably a beam bending angle comprised between 3°and 15°.

5. Electron accelerator according to any of claims 1 to 4, **characterized in that**:

- the outer conductor (11) and the inner conductor (12) are coaxial cylindrical conductors of axis A, both cylindrical conductors being shorted at their distal ends with respectively a top conductive closure (13) and a bottom conductive closure (14),
- the electron source (20) is adapted to inject the beam of electrons (40) into the cavity (10) following a radial direction in a median transversal plane (MP) of the cavity (10),
- the RF source (50) is adapted to generate the transverse electric field (E) into said cavity so as to accelerate the electrons of the electron beam (40) a plurality of times into the median transversal plane (MP) and according to successive trajectories following angularly shifted diameters of the outer cylindrical conductor (11),
- the nominal path is in the median transversal plane (MP);

6. Electron accelerator according to any of claims 1 to 5, **characterized in that** the kicker magnet (80) is configured to deviate the electron beam away from said nominal path towards the intermediate accelerator output (41 a) while said kicker magnet is switched ON.

7. Electron accelerator according to claim 6, **characterized in that** said plurality of deflection magnets of the at least one of the beam deflectors (30) comprises a main deflection magnet (81, 81 b) arranged downstream of the kicker magnet (80) and **in that** said main deflection magnet (81, 81 b) is configured:

- to receive the electron beam from the kicker magnet and to redirect the received electron beam according to the nominal path to the entry port (16) of the cavity while the kicker magnet is switched OFF, and
- to receive the electron beam from the kicker magnet and to redirect the received electron beam to another direction while the kicker magnet is switched ON.

8. Electron accelerator according to any of claims 1 to 5, **characterized in that** the kicker magnet (80) is configured to deviate the electron beam away from said nominal path towards the intermediate accelerator output (41 a) while said kicker magnet switched

OFF.

9. Electron accelerator according to claim 8, **characterized in that** said plurality of deflection magnets of the at least one of the beam deflectors (30) comprises a main deflection magnet (81, 81 b) arranged downstream of the kicker magnet (80) and **in that** said main deflection magnet (81, 81 b) is configured:

- to receive the electron beam from the kicker magnet and to redirect the received electron beam according to the nominal path to the entry port (16) of the cavity while the kicker magnet is switched ON, and
- to receive the electron beam from the kicker magnet and to redirect the received electron beam to another direction while the kicker magnet is switched OFF.

10. Electron accelerator according to any of preceding claims, **characterized in that** the kicker magnet (80) is the first deflection magnet in said sequence of deflection magnets.

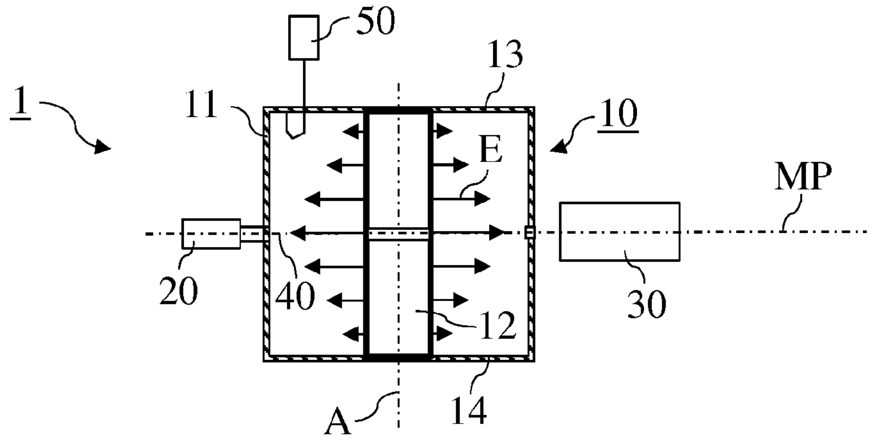
11. Electron accelerator according to any of preceding claims, **characterized in that** the control unit (90) is configured to vary the time during which the kicker magnet (80) is switched ON and/or to vary the time during which the kicker magnet (80) is switched OFF.

12. Electron accelerator according to any of preceding claims, **characterized in that** the control unit (90) is configured to repeatedly switch the kicker magnet (80) ON and OFF in a periodic fashion at a switching frequency.

13. Electron accelerator according to any of preceding claims, **characterized in that** the control unit (90) is configured to keep the beam deflection magnets of a beam deflector, other than the kicker magnets, permanently switched ON while the kicker magnet (80) is switched ON and OFF.

14. Material detection system comprising an electron accelerator (1) according to any of preceding claims, a first RX conversion target (101) and a second RX conversion target (102) arranged in the paths (41, 42) of the electron beams coming from respectively the intermediate and the main accelerator outputs (41 a, 42a), a first RX detector (110) and a second RX detector (120) arranged in the paths of the X-rays generated respectively by the first and the second RX conversion targets (101, 102).

15. Material irradiation system comprising an electron accelerator (1) according to any of preceding claims, said electron accelerator being configured for irradiating a material product (600) with the electron beam coming from the main accelerator output (42a) and/or from the intermediate accelerator output (41 a).


50
13
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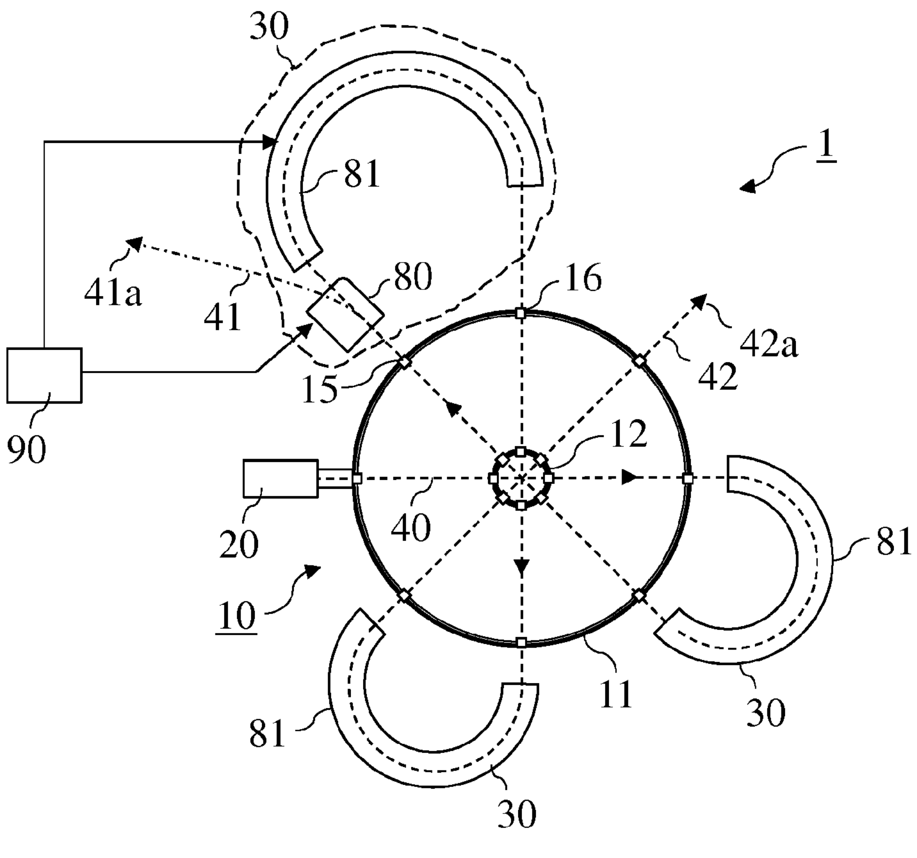
11
10
E
MP
20
40
30
12
A
14

Fig. 1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1
81
41a
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42a
42
15
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12
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40
81
10
11
30
81
30

Fig. 2

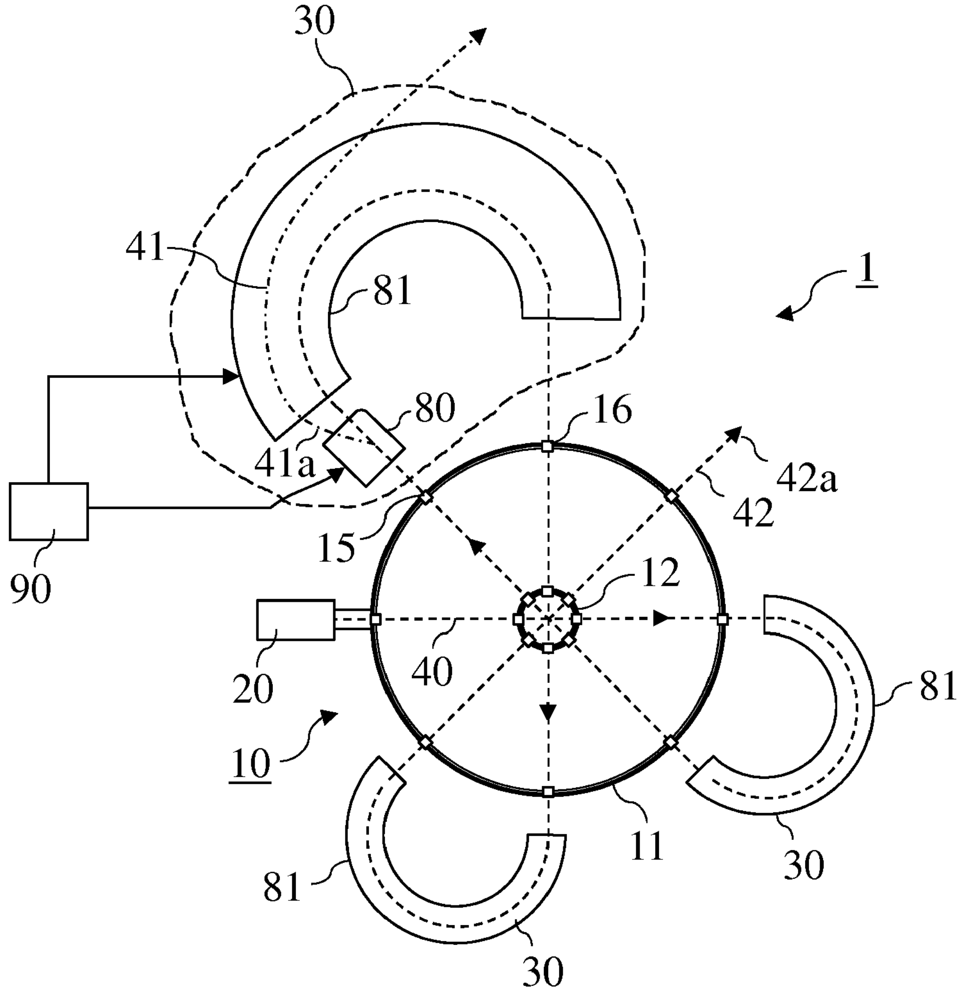
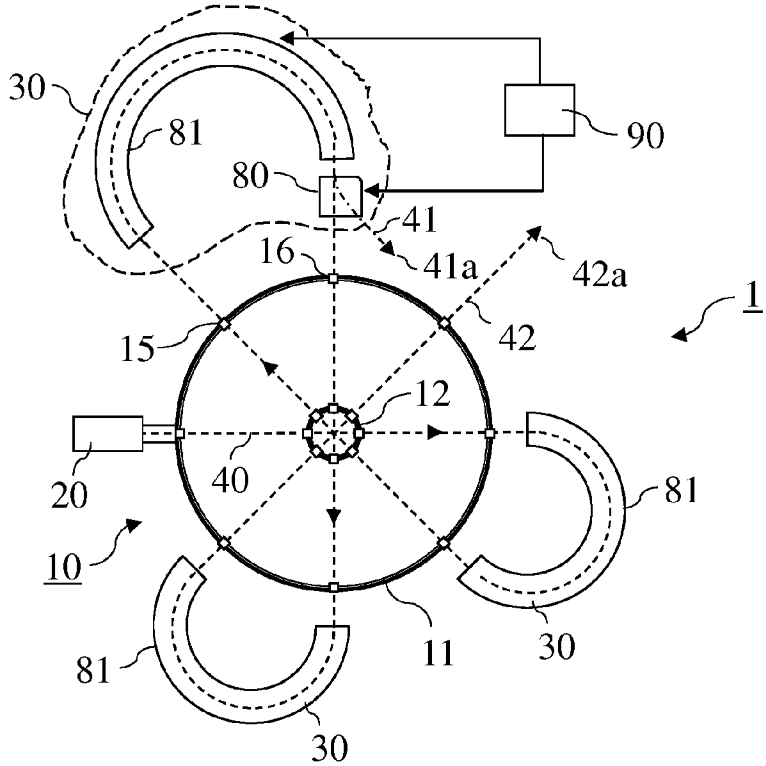


Fig. 2a

Fig. 3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81
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90
41
16
41a
42a
15
42
1
12
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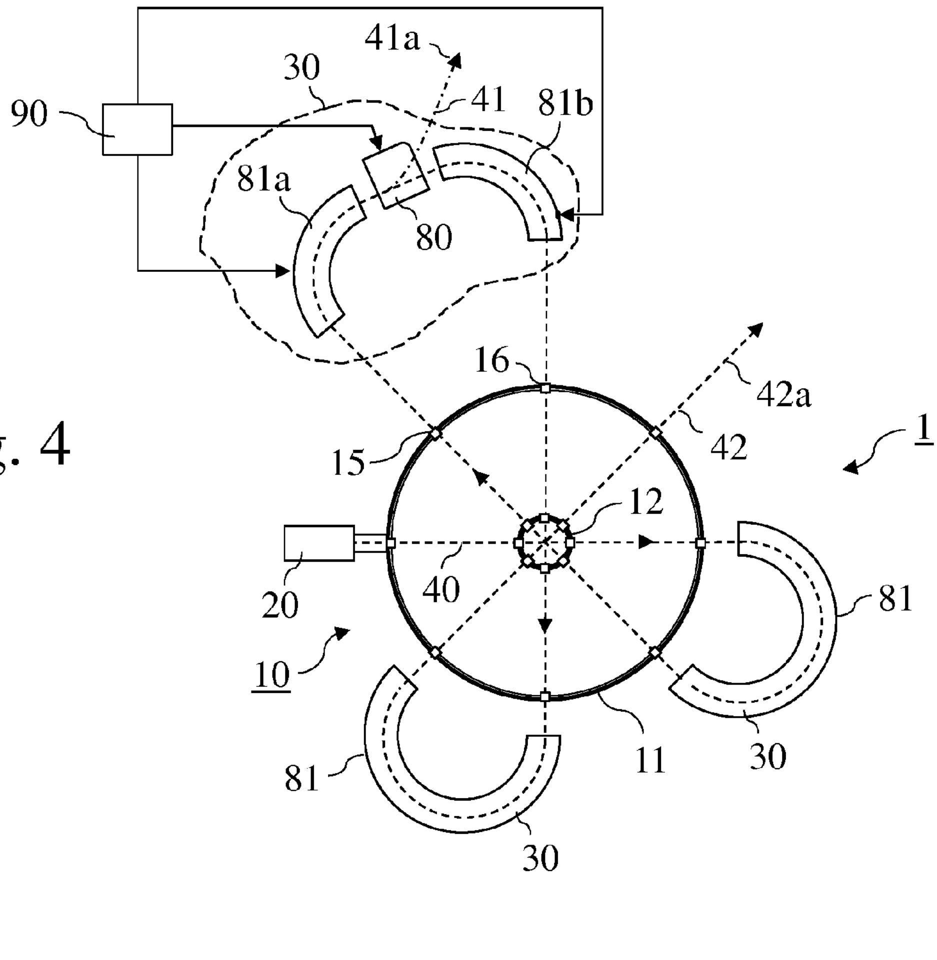
40
81
10
81
11
30
30

Fig. 4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30
41
81b
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81a
80
16
42a
15
42
1
12
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40
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10
11
30
81
30

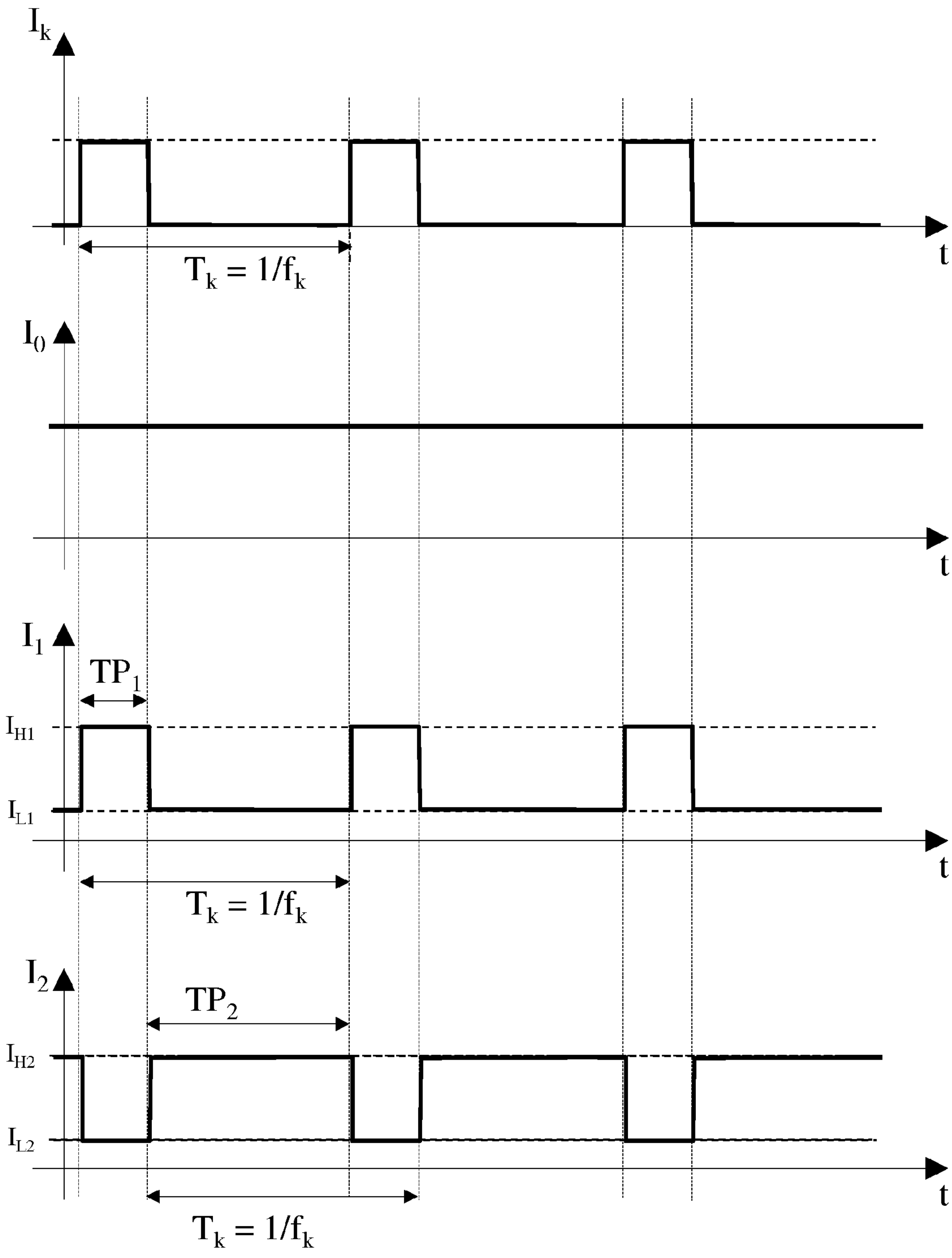
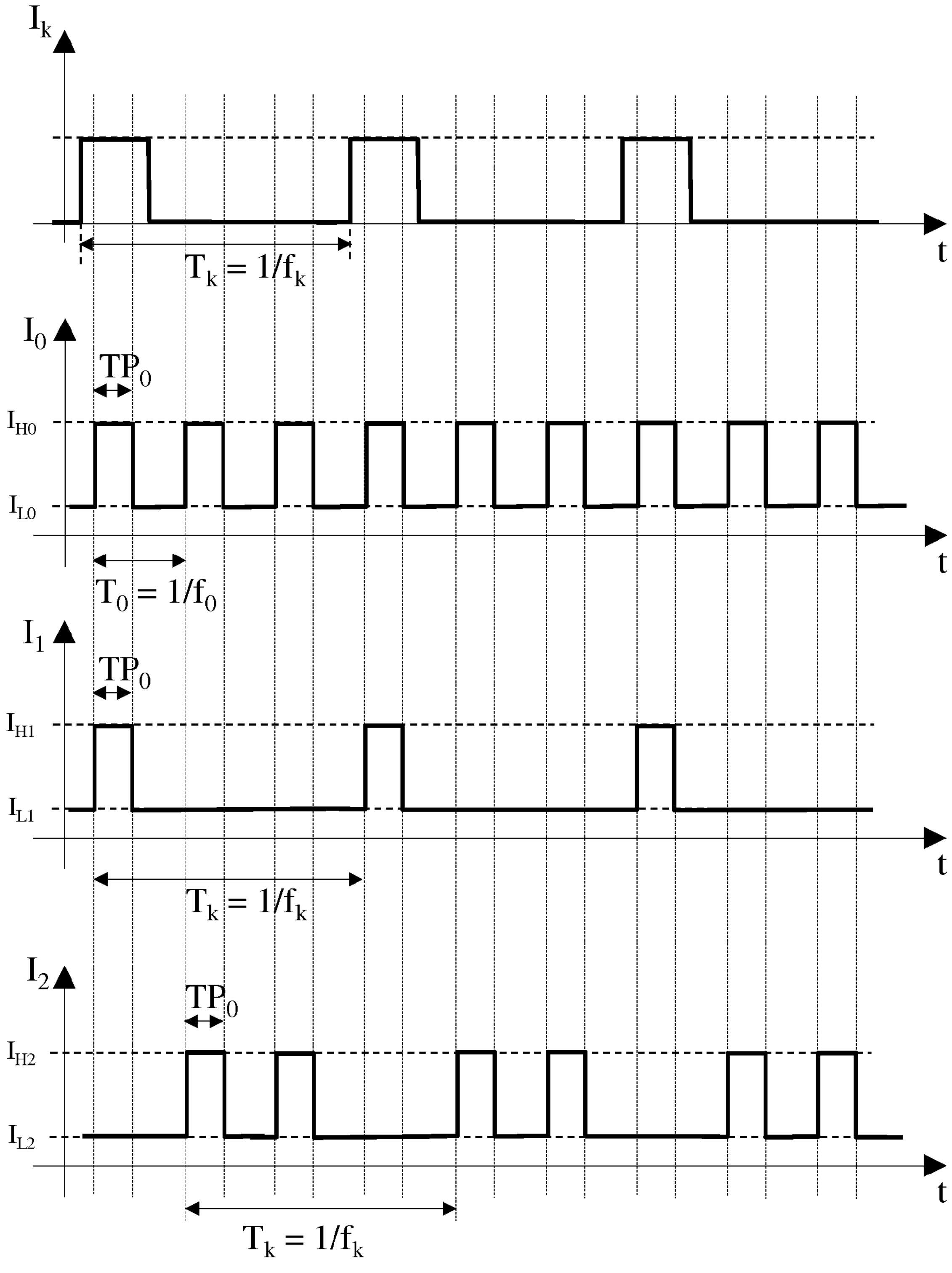


Fig. 5a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IH0
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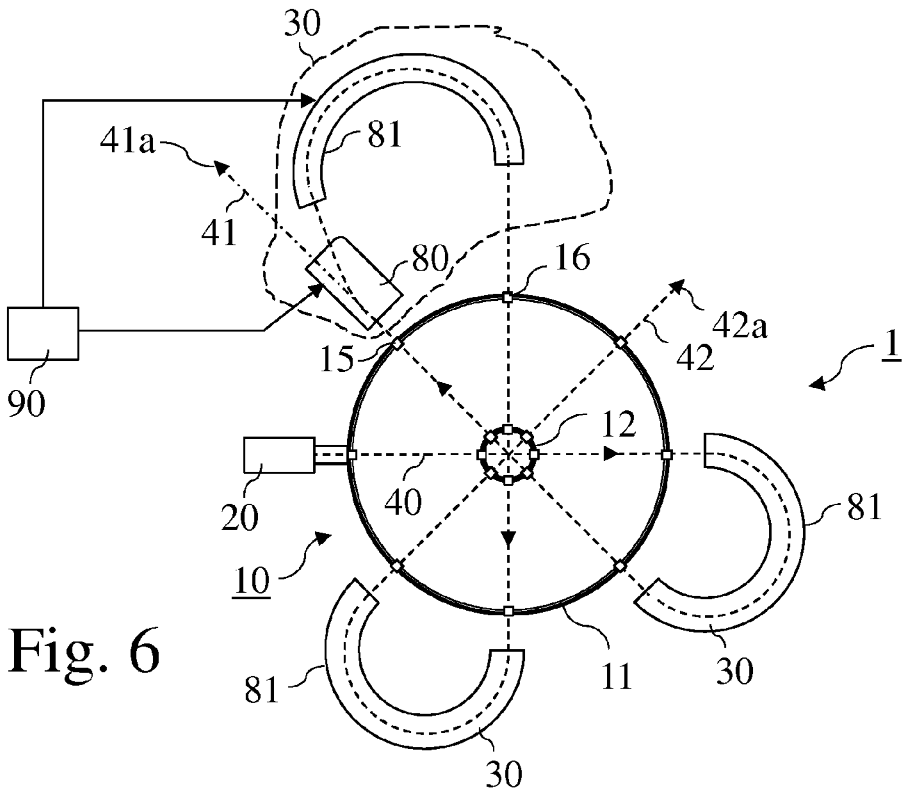
Tk = 1/fk

Fig. 5b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41a
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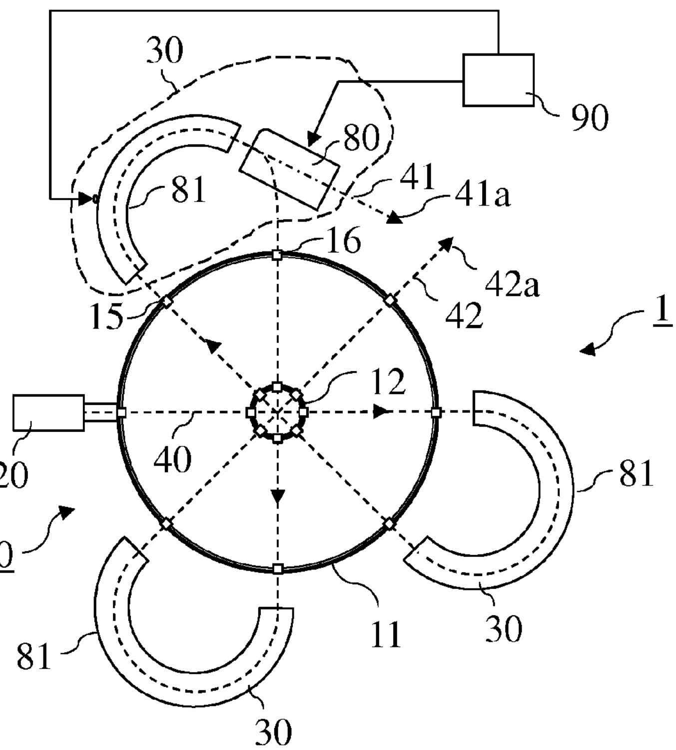
30
30

Fig. 6


30
90
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42a
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10
81
11
30
30

Fig. 7

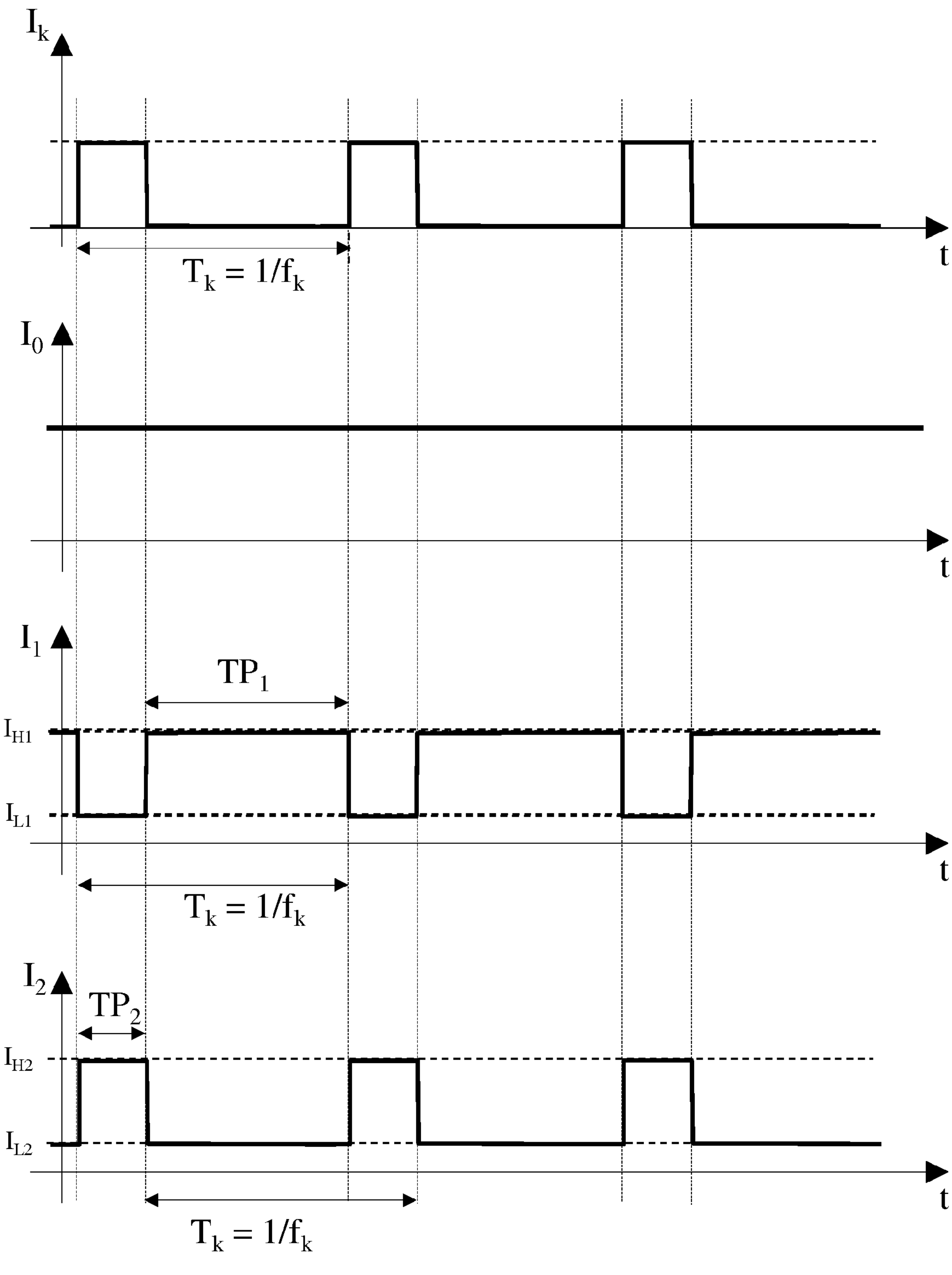
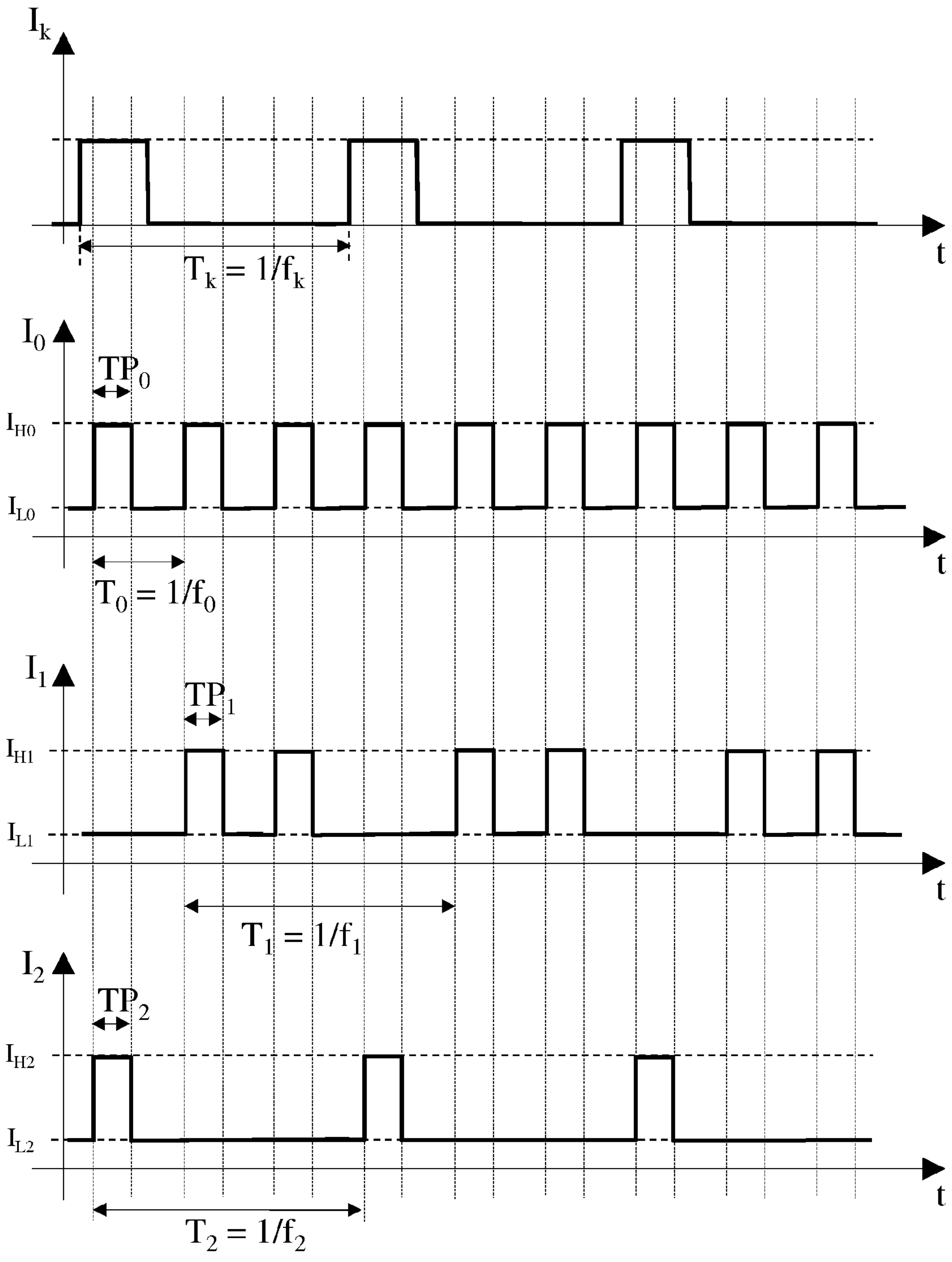


Fig. 8a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I_{H0}
I_{L0}
t
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TP_1
I_{H1}
I_{L1}
t
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I_2
TP_2
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I_{L2}
t
$T_2 = 1/f_2$

Fig. 8b

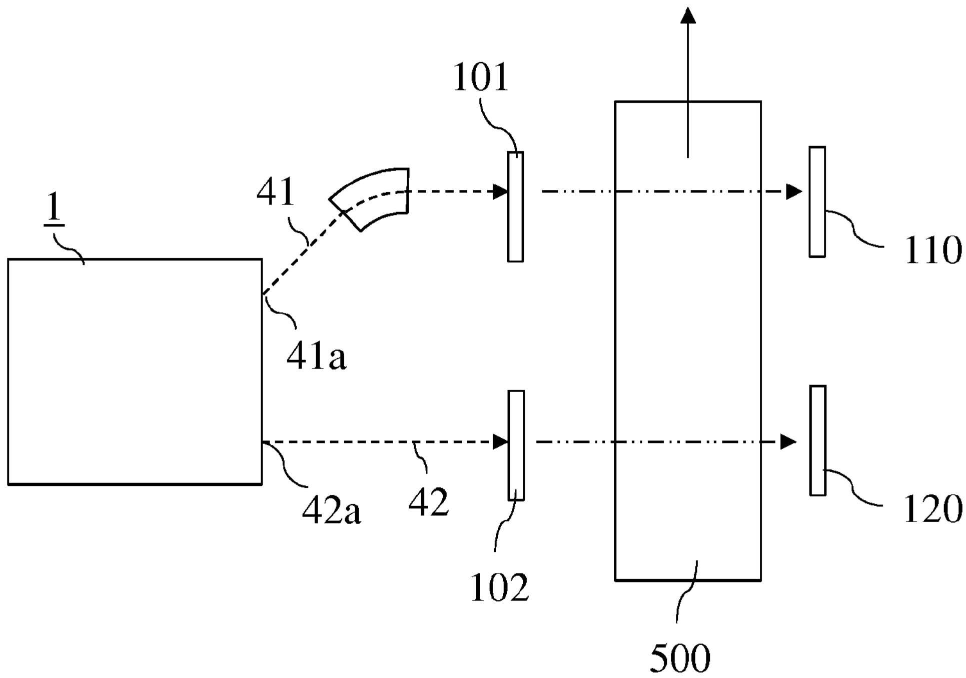

Fig. 9

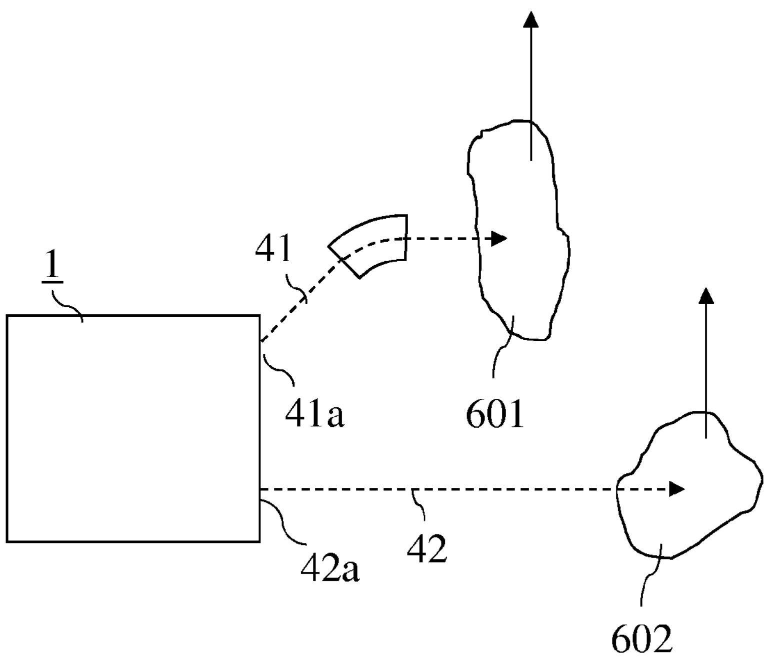

Fig. 10

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EUROPEAN SEARCH REPORT

Application Number
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			H05H

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	16 October 2015	Clemente, Gianluigi

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EUROPEAN SEARCH REPORT

Application Number
EP 15 17 0721

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A	* figures 4,6 * * column 3, line 44 - column 5, line 13 * -----	1,2,5	TECHNICAL FIELDS SEARCHED (IPC)
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A	* figure 1 * * page 5, line 17 - line 26 * -----	1	
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
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