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(71) Applicant: **Pécsi Tudományegyetem**
7622 Pécs (HU)

(72) Inventors:
- **HEBLING, János**
H-7635 Pécs (HU)
- **ALMÁSI, Gábor**
H-7761 Kozármisleny (HU)
- **TIBAI, Zoltán**
H-7633 Pécs (HU)
- **FÜLÖP, József András**
H-7635 Pécs (HU)

(74) Representative: **Szabo, Zsolt**
Danubia
Patent & Law Office LLC
Bajcsy-Zsilinszky út 16
1051 Budapest (HU)

(54) ## METHOD AND SETUP TO PRODUCE RELATIVISTIC ELECTRON BUNCHES

(57) The invention relates to a novel technique for the acceleration of electrons to relativistic energies.

According to the technique, electrons (40) of low initial energy are generated by an electron source (17). At the location of the electrons, at least two THz pulses (10, 20) are provided synchronized to an instant of time of the electron generation. By superimposing electric fields of the at least two THz pulses, a non-steady resultant electric field is generated at the location of the electrons and the electrons are brought into interaction with the resultant electric field accordant to a temporal evolution of the electric field strengths of the THz pulses, thereby increasing electron energy, and thus, accelerating the electrons along a propagation path (30) to relativistic energies. Here, the provision of the THz pulses and the instant of time of the electron generation are synchronized to one another by providing, at the location of the electrons at the instant of time of the electron generation, each of the THz pulses by a THz pulse with an electric field of predetermined phase, said phase being the same for each THz pulse, and by generating the non-steady resultant electric field as an electric field with an electric field strength having a direction that represents an accelerating influence on the electrons.

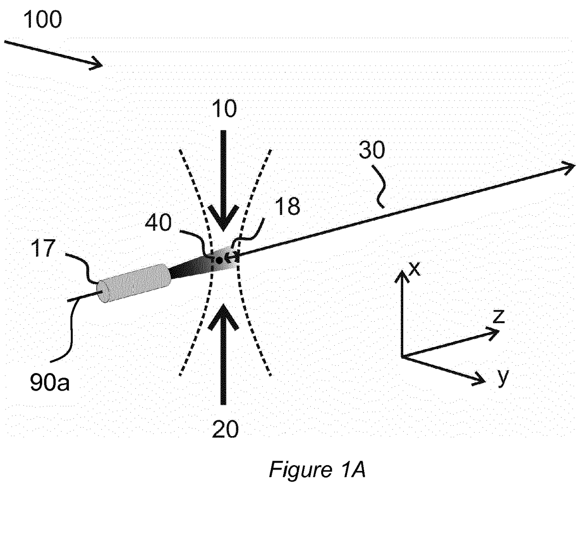

Figure 1A

Description

[0001] The present invention relates to a method and a setup to produce relativistic electron bunches. In particular, the present invention relates to methods and setups to implement the methods which allow to accelerate electrons in an electron bunch to relativistic velocities in a highly efficient manner and basically from any initial electron velocities.

[0002] The velocity of relativistic electrons is about more than 90 percent of the speed of light. Production of electron bunches of such electrons is possible for almost about five decades now, amongst others by means of using electron guns. To build electron guns, however, is rather expensive. Therefore, in the last decade reasonable amount of attention has been paid to the development of cheaper electron accelerating techniques.

[0003] According to a possible solution, to accelerate electrons, laser pulses are used in accelerators of special design, an example of which is the dielectric accelerator proposed in the paper by T. Plettner et al. "Proposed few-optical cycle laser-driven particle accelerator structure" (see Phys. Rev. Spec. Top. Accel. Beams 9, 111301 (2006)). As far as the concept is concerned, a dielectric accelerator is a device in which a laser beam is focused on a pair of centrally positioned grids made of a dielectric material from both sides thereof, as a result of which a non-steady electric field of alternating sign arises between the grids. To increase further the velocity of relativistic electrons, the relativistic electrons are directed through a region located between said grids, where due to the electromagnetic field that builds up between the grids, the electrons get accelerated. Although, studies aiming at such dielectric accelerators are still in initial stage, it is already apparent that due to the size in the micron range, such accelerators are suitable for accelerating a very small amount of charge (that is, a small number of electrons) at a time. From the point of view of practical applicability of the dielectric accelerator, this represents a huge disadvantage.

[0004] It is known that accelerating electrically charged particles (such as e.g. protons, ions) can also be achieved by means of applying terahertz (THz) pulses if the THz pulses to be used for the acceleration have got adequately high energy and peak electric field strength. Such a solution is disclosed e.g. in European Patent no. 2,848,099 B1, according to which charged particles are accelerated by the evanescent field of a THz radiation arising in a region between two identical non-linear optical crystal blocks arranged in a given distance apart from one another. The THz radiation is provided by THz pulses generated by either splitting the output of a single THz radiation source, or simultaneously operating two THz radiation sources that are appropriately synchronized. Destruction threshold of the material of the optical crystal blocks, however, sets limits to practical applicability of this solution as it limits the energy of the applicable THz pulses from above. Accordingly, the solution disclosed in said European patent is not suitable for the efficacious acceleration of relativistic electrons.

[0005] The interaction between THz pulses and charged particles is well known in the art. International Publication Pamphlet no. WO2013/024316 A2 teaches a method and an arrangement suitable for generating electromagnetic radiation by means of modulating relativistic particles, electrons, with THz pulses. Accordant to this technique, said relativistic electrons move along a harmonic path and thereby emit a radiation during their accelerating movement. In the arrangement, the direction of the field strength in the THz pulses, and thus the displacement of the electrons, is perpendicular to the initial velocity vector of the electrons. As the accelerating and decelerating forces acting on the electrons are compensated, the energy, and hence speed, of the electrons passing through the arrangement will not increase significantly. In the arrangement, an electromagnetic radiation with a central wavelength of 0.1 to 100 nm can be obtained by means of THz pulses having a peak electric field strength in the MV/cm order of magnitude. Nevertheless, the arrangement is still not suitable for accelerating the electrons passing therethrough.

[0006] As a consequence of the tilted-pulse-front technique applicable in the case of lithium niobate ($LiNbO_3$) crystals, the energy of the THz sources has increased about seven orders of magnitude since the 1990's and attained the energy of 100 μJ. Further increase of this energy can be achieved by means of various techniques, such as the application of long pulse duration excitation, cryogenic temperatures as well as a contact grating. By exploiting the techniques mentioned here, a source energy of several 10 mJ, as well as a peak electric field strength of more than 10 MV/cm can be accomplished, that already make it possible to accelerate electrons as well.

[0007] The paper by W.R. Huang et al. "Toward a terahertz-driven electron gun" (see Sci. Rep. 5, 14899 (2015)) proposes a method and an arrangement to manipulate non-relativistic electrons by means of THz radiation. Here, a cathode made of copper plate emits electrons upon being irradiated with a (green) laser. The electrons being emitted from the metal are acted upon by a single-cycle THz pulse with the peak electric field strength of 0.72 MV/cm which results in the acceleration of the electrons. As a consequence of being accelerated, the electron energy attains several 10 eV. Based on simulation data, the authors come to the conclusion that an electron bunch of about 100 keV may be obtained if a THz pulse with the peak electric field strength of 20 MV/cm is made use of. However, the calculation takes into account for the effect of only a single THz pulse on the electrons leaving the cathode and in an asymmetric configuration. This influences significantly the transverse displacement of the accelerated electrons and the actual extent of the acceleration, as well as the synchronized behaviour of the electron bunch, which is highly disadvantageous in practice.

[0008] The paper by L.J. Wong et al. "Compact electron acceleration and bunch compression in THz waveguides" (see Opt. Express 21, 9792-9806, (2013); arXiv: 1311.57811) provides detailed numerical calculations for the manipulation of electron bunches by means of THz electromagnetic radiation, in particular regarding the compression and the acceleration of the bunches to relativistic velocities (i.e. to energies about 1 to 10 MeV). In the arrangement discussed here, the interaction between the THz electromagnetic radiation and the electron bunch to be accelerated takes place in a waveguide that has a specific cylindrical shape, wherein the electron bunch to be accelerated has to have a kinetic energy of several tens of keV already before actually commencing the acceleration; that is, the arrangement concerned can substantially be used to accelerate pre-accelerated electron bunches further, but it is not suitable for accelerating electrons with about zero initial kinetic energy.

[0009] In light of the above, the object of the present invention is to develop a generally applicable electron acceleration scheme, especially a method and a setup, that allows to accelerate/post-accelerate one or more electrons in a single stage at a time or in more consecutive stages by making use of more THz pulses, preferably in vacuum, with the application of no waveguide(s) and even in the case of electrons that are initially basically standing, i.e. not in motion.

[0010] Another object of the present invention is to provide methods and setups to accelerate electrons/bunches of electrons of e.g. small energies, optionally electrons of basically zero velocity (at most several eV in kinetic energy) and electron bunches comprising such electrons, optionally in a progressive manner, i.e. in several consecutive steps, or alternatively to post-accelerate such electrons/electron bunches.

[0011] A yet further object of the present invention is to develop electron accelerator setups and methods, by means of which such an electron bunch can also be accelerated efficaciously that has a total electric charge higher than what can nowadays be attained in electron bunches to be accelerated.

[0012] A yet further object of the present invention is to enhance synchronicity between the creation and the acceleration of electrons in an electron bunch subjected to acceleration and/or to narrow the energy distribution of the electrons in the bunch, or putting this another way, to mono-energize the electron bunch simultaneously with its acceleration, and thus to increase the efficiency of the acceleration when relativistic electron bunches, in particular ultrashort relativistic electron bunches are accelerated.

[0013] In light of the above, the present invention, in its first aspect, relates to a method to accelerate electrons to relativistic energies by means of THz pulses in accordance with the method of claim 1. Preferred further variants of the method according to the invention are defined by dependent claims 2 to 14.

[0014] The present invention, in its second aspect, relates to a setup to accelerate electrons to relativistic energies by means of THz pulses in accordance with the setup of claim 15. Possible further preferred embodiments of the setup according to the invention are set forth in dependent claims 16 to 20.

[0015] Possible further objects to be achieved by and advantages of the present invention will be apparent in light of the following description.

[0016] In our studies we have reached the conclusion that the electrons in a previously created electron bunch can be accelerated by means of focusing THz pulses propagating essentially opposite to one another on the spatial location of said electron bunch. The THz pulses propagating essentially opposite to one another (from now on the THz pulse pair) travel in opposite directions to one another basically along a straight line, meet at the location of the electron bunch to be accelerated and get superimposed there. Here, the THz pulses, or rather the overall non-steady electromagnetic field of the resultant pulse arising due to the superimposition has got on influence on the motion of the electrons; the electrons get accelerated in a direction opposite to that of the overall electromagnetic field. As far as the acceleration is concerned, it is advantageous if the electric field strengths of the THz pulses travelling essentially opposite to one another point into the same direction, while the magnetic field strengths of the THz pulses point into opposite directions and thus the magnetic fields of the pulses practically cancel each other. To this end, such THz pulses are required which are generated by the same THz source or through a division/split performed suitably (e.g. optically, by means of one or more beam splitters) at a certain point of the pulses' propagation path or by separate THz sources operated properly synchronized with each other. Here, and from now on, the terms "THz electromagnetic radiation" and "THz radiation" and "THz pulse" refer, as it is known to a skilled person in the art, to a radiation and/or a pulse in the 0.1 to 10 THz domain of the electromagnetic spectrum.

[0017] To accelerate electrons, one can apply more than one of such pairs, capable of accelerating electrons, of THz pulses travelling essentially opposite to one another at the same instant of time (that is, at a certain spatial location of the electron bunch) or at consecutive locations along the propagation path of the accelerated electron bunch (that is, at different spatial locations of the electron bunch and thus at different instants of time). Hence, (i) the amount of energy fed into the electron bunch at a given spatial location (that is, in a single acceleration stage) can be increased and/or (ii) a gradual (post-)acceleration of the electron bunch can be accomplished in more than one separate and independent stages. In the case of a single stage acceleration, straight lines each representing a propagation direction of a pulse pair, or - putting this another way - the optical axis of an individual pulse, lie in a plane that is essentially perpendicular to the propagation path of the electrons/electron bunch to be accelerated and form definite angles with one another in the plane. Preferably, these angles are equal with one another, however this is not a requisite, and thus the pulse pairs are applied in a rotational symmetric configuration. In case of a consecutive multiple stage acceleration, one or more THz pulse pairs are focused on a region situated at the actual spatial location of the electron bunch in a synchronized manner at arbitrarily chosen given distances along the propagation path of the electrons/electron bunch, wherein the dimension of said region is in the same order of magnitude as the wavelength of the individual THz pulses of the pulse pair(s), and preferably said region has got a dimension basically equal to said wavelength. Synchronization of the focusing of the THz pulses on the electron bunch is performed in such a way that the focused pulse pair(s) and the electrons/electron bunch arrive simultaneously (precisely at the same instant of time) at every chosen location of the propagation path, that is, the spatial locations of the superimposition of the electromagnetic fields of the THz pulses always coincide with the spatial locations of the electrons/bunch of electrons to be accelerated along the propagation path of said bunch. In this case, as a result of the interaction between the electron bunch and the electric field of the resultant pulse, an efficient acceleration of the electron bunch is obtainable if the electric field of the resultant pulse is of appropriate phase, i.e. the electric field has a direction which represents an accelerating influence on the electrons or just accelerates the electrons.

[0018] In our studies we have also come to the conclusion that the acceleration of electrons/bunches of electrons can also be performed within the scheme according to the present invention in such a case, wherein straight lines representing the propagation directions of the individual pulses of THz pulse pairs, or alternatively the optical axis of each individual THz pulse, are in a plane that also contains the propagation path of said electrons/bunches of electrons and form an angle with one another in the plane that ranges from at least 60° to at most 180°.

[0019] In our studies we have also come to the conclusion that from the point of view of electron acceleration according to the invention performed in the above discussed configurations it is especially advantageous if the number of the optical cycles of the THz pulses is preferably ranges from one to two, is at most about two, preferentially about one and a half, and most preferably substantially one. In the case of THz pulses of such a short duration, the electrons to be accelerated will sense a larger proportion of the "accelerating" portion of the overall electric field (i.e. which points opposite to the direction of propagation of the electrons) of the resultant pulse that arises as a result of the superimposition of the THz pulses than the "decelerating" portion of said overall electric field (i.e. which points into the direction of propagation of the electrons), and thus the energy and the velocity of the electrons will increase.

[0020] Compared to electron acceleration induced by laser pulses of visible or near visible wavelengths, one of the advantages of electron acceleration by means of THz pulses according to the present invention is that the wavelengths of the THz pulses are larger by several orders of magnitude. Therefore, an electron bunch of proportionally greater transversal size, and thus a larger amount of total electric charge can be accelerated by means of THz pulses. Moreover, the larger spatial size of THz pulses also facilitates that the electron bunch is accelerating/accelerated as a whole, that is, the individual electrons forming the bunch will accelerate more or less to the same extent. Consequently, the extent of longitudinal spreading of said electron bunch along the propagation path decreases, and hence the monoenergetic behaviour of the bunch improves.

[0021] Furthermore, due to a longer period of time of the THz pulses, the acceleration period available for accelerating the electrons will also be longer by several orders of magnitude. As a result of the longer period of time, a synchronization with higher precision can be achieved between the phase of the THz pulses used for the acceleration and the electrons/bunch of electrons, as it will be discussed later on in more details.

[0022] The invention is discussed now in more details with reference to the accompanying drawings, wherein

- Figures 1A and 1B are schematic representations of the electron acceleration scheme according to the present invention for an electron accelerator setup comprising a single acceleration stage with the application of one pair and at least two pairs, respectively, of THz pulses that travel essentially opposite to one another;
- Figure 2A shows, for a single pair of pulses, the spatial shape of the electric field strength of the THz pulses used in the electron acceleration scheme according to the invention and of the resultant pulse arising due to superimposition of said THz pulses;
- Figure 2B represents the change in energy of electrons accelerated by the pair of THz pulses shown in Figure 2A in the duration of said THz pulses in the case of electrons with an initial kinetic energy of 0 keV (i.e. with the velocity of v=0 m/s, standing electrons) for different THz beam dimensions;
- Figure 3 is a schematic representation of a possible embodiment of an electron acceleration setup for implementing the electron acceleration scheme according to the invention comprising a single acceleration stage with the application of a single pair of THz pulses;
- Figure 4A is a schematic representation of the electron acceleration scheme according to the invention comprising more than one consecutive acceleration stages with the application of a single pair of THz pulses in each acceleration stage;
- Figure 4B is a schematic representation of a possible embodiment of an electron acceleration setup for implementing the multi-stage electron acceleration scheme shown in Figure 4A;
- Figure 5 represents the energy of electron bunches accelerated in the electron acceleration setup of Figure 4B as a function of the number of applied acceleration stages for electron bunches of different initial kinetic energy and the application of THz accelerating pulses of different frequency; and
- Figure 6 is a schematic representation of the electron acceleration scheme according to the invention implemented

as an acceleration setup comprising a single acceleration stage only, wherein the THz pulses used to accelerate the (bunch of) electrons and the propagation path of the (bunch of) electrons to be accelerated form a given angle.

[0023] Figure 1A represents schematically a preferred embodiment of an electron acceleration setup 100 implementing the acceleration scheme according to the invention, wherein the acceleration of a bunch 40 of electrons takes place in a single acceleration stage by means of a single pair of THz pulses 10, 20 that travel essentially opposite to one another. Here, an electromagnetic standing wave is created with the two THz pulses 10, 20 in a propagation path 30 of the bunch 40 of electrons; the electrons come from a source 17 of electrons, in particular, from a gas jet or a metallic layer irradiated with a laser pulse (in this case the electrons preferably have got an energy of several eV's, but at most about 10 eV) or from an electron gun (such electrons preferably have got an energy of about 0 to 60 keV, but at most 100 keV). To this end, a single pair of THz pulses, that is two THz pulses 10, 20 travelling essentially opposite to one another and consisting of several optical cycles each are focused on the bunch 40 of electrons, or rather the spatial region occupied by said bunch 40 of electrons, from a direction perpendicular to the propagation path 30. The number of optical cycles contained in the applied THz pulses 10, 20 ranges preferably from one to two, it is preferably about two, more preferably about one and a half, and most preferably about one. An advantage of pulses 10, 20 travelling opposite to one another is that the magnetic field strengths of such pulses cancel each other at the spatial location of the bunch 40 of electrons, and hence, no forces at right angle to the propagation path 30 of the electrons act. In Figure 1A, the dashed curves represent the radius of each THz pulse 10, 20 (that is, the distance at which the amplitude of the electric field strength falls to 1/e of its value along the pulse). The minimal radius of the THz pulses 10, 20, i.e. the so-called beam waist 18, is preferably focused on the actual spatial location of the bunch 40 of electrons (for example, on the place of the electron generation), thereby providing the greatest possible electric field strength at the location of the bunch 40 of electrons.

[0024] The effect of the THz pulses 10, 20 applied in the setup 100 according to the invention on the electron bunch 40 is determined by the relativistic Lorentz equation of

$$\frac{d(\gamma m\vec{v})}{dt} = q \cdot (\vec{E}(r,t) + \vec{v} \times \vec{B}(r,t)), \qquad (1)$$

known from literature, where γ is the relativistic factor, q is the electric charge, $\vec{v}$ is the velocity of the electrons, $\vec{E}$ is the electric field strength and $\vec{B}$ is the magnetic induction of the resultant laser field arising in the setup 100 as the superimposition of said THz pulses 10, 20; this laser field acts on the electrons in the bunch 40. Accordant to equation (1), the resultant field strength determines, in harmony with its direction, the acceleration direction of the electrons; thus, the setup itself used for accelerating electrons can be considered as a basically longitudinal acceleration configuration.

[0025] In what follows, the basic concepts of electron generation and electron acceleration by means of the scheme according to the present invention are discussed in detail on the basis of Figure 2A with reference to the setup 100 illustrated in Figure 1A.

[0026] Figure 2A shows the spatial shape of the electric field strengths of the THz pulses used to electron acceleration according to the invention for a single pair of pulses. The initial electron bunch is generated at the spatial position of x = 0. Then, said electron bunch is acted upon, in accordance with equation (1), by the overall electromagnetic field (resultant field) of the two THz pulses (left pulse, right pulse) located at an angle of essentially 180° in terms of the propagation directions of the pulses; due to the interaction, the electrons in the bunch gain a given amount of energy in total. Figure 2B illustrates the change in energy of the electrons accelerated by the pair of THz pulses over the duration of the THz pulses (that is, as long as the interaction operates) in the case of electrons with an initial energy of 0 keV (that is, standing electrons with the velocity of v=0 m/s) for the application of THz pulses with various beam sizes and focusing levels, i.e. with different beam waists w.

[0027] As it is shown in Figure 2A, the phase of the applied THz pulse(s) is synchronized to the instant of time of the electron generation in such a way that the field strength(s) of the incoming THz pulse(s) is(are) about 0 MV/cm at the place of the electron generation; thus, the overall electric field strength will also be about 0 MV/cm in this spatial position. Then, the electric field strength in the incoming THz pulse(s), and hence the overall electric field strength, gets larger and larger within the optical cycle of each of the pulses that results in the acceleration of the electrons. The basis for an efficacious electron acceleration lies in the proper synchronization. Synchronization can be accomplished if the laser used to generate the bunch of electrons and the laser used to generate the THz pulses are provided by the same laser equipment. The two generation processes can be coordinated and controlled via appropriately choosing and suitably adjusting (in a manner generally known by a skilled person in the art) the path length of the laser pulses applied to generate the THz pulses, as well as the path length of the THz pulses themselves. It should be here noted that the bunch of electrons can be accelerated in this case until the electrons forming it interact with the accelerating portion of the resultant pulse obtained by the superimposition of the THz pulses. This holds until the electric field strength of the resultant pulse is negative; however, the largest extent of acceleration of the electrons can be achieved if the interaction starts to operate between the electrons and the overall electric field of the resultant pulse at the instant when the electric field strength of the resultant pulse changes from positive values to negative ones.

[0028] Figure 3 shows a preferred exemplary embodiment of a setup 100a to accomplish synchronization and electron acceleration. Here, a laser pulse 90a generated by a high-energy laser 90 (with an output falling in the range 1-5000 mJ and being also capable of handling the task of synchronization) is directed through a beam splitter 89, by means of which the beam of the laser pulse 89a is divided in two parts, in particular, to a first beam 90a1 and a second beam 90a2. The first beam (pulse) 90a1 is then led to the source 17 of electrons and is used to generate the bunch 40 of electrons. The second beam (pulse) 90a2 is directed through a second beam splitter 88, by means of which it is divided in two further parts, namely to a first beam 90a21 and a second beam 90a22. The THz pulses 10, 20 used for the electron acceleration are generated by said first and second beams 90a21 and 90a22, respectively, in a manner known to a skilled person in the art, that is, by optical means (source of THz pulses) 15, 25 used to perform processes suitable for creating THz pulses, such as e.g. through THz generation based on the tilted-front-pulse excitation technique, discussed e.g. in the papers by J. Hebling et al. "Velocity matching by pulse front tilting for large area THz-pulse generation" (see Opt. Express, 10(21), 1161 (2002)) and by L. Pálfalvi et al. "Numerical investigation of a scalable setup for efficient terahertz generation using a segmented tilted-pulse-front excitation" (see Opt. Express, 25, 29560 (2017)). In our studies we have reached to the conclusion that acceleration of a bunch 40 of electrons with a charge density falling in the range 10^3-10^{11} nC/cm^3 can be performed with THz pulses 10, 20 having peak electric field strengths falling in the range 0.05-500 MV/cm; such THz pulses can be generated by THz generation techniques taught in the above referenced two publications.

[0029] By properly adjusting the optical path lengths travelled by the beams 90a1, 90a21, 90a22, synchronization of the instant of generation of the bunch 40 of electrons to the instant of change of sign of the overall electric field strength of the THz pulses 10, 20 propagating essentially opposite to one another can be performed in a controlled manner. In this way, through said synchronization, one achieves that the bunch 40 of electrons "senses" an accelerating electric field strength at the instant of its generation. During the influence of the THz pulses 10, 20 on the electron(s) in the electron bunch 40 the energy of the electrons increases monotonically (acceleration period) until the overall electric field strength of the THz pulses 10, 20 changes its sign. After the sign change have taken place, the velocity and the kinetic energy of the electrons decrease (deceleration period), as it is clearly shown in Figure 2B. The change in energy of the electrons continues until the field of the resultant pulse produced by superimposing the THz pulses 10, 20 acts on the electrons. Preferably, the action of the decelerating portion of said resultant pulse is decreased by means of focusing the THz pulses 10, 20, that is, by diminishing the size of the beam waist 18 (see Figure 1A). Here, focusing of the THz pulses 10, 20 means that said pulses are concentrated into a spatial region that has a size substantially in the order of magnitude of, preferably equal to the wavelength of the THz pulses 10, 20. Said focusing is performed by a suitable lens or a parabolic mirror in a manner known by the skilled person in the art. To achieve the possible largest gain in energy of the electrons in the bunch 40, the spatial position of the bunch 40 of electrons and the major parameters (such as the beam waist, peak electric field strength and wavelength) of the THz pulses 10, 20 are optimized.

[0030] Practical applicability of the setup 100a discussed above is fully supported by numerical simulation data we obtained. To perform the simulation, a software code is used which uses an approximation as to each of the THz pulses 10, 20 in the form of a beam having Gaussian profile, and solves the differential equation (1) representing the equation of motion for the electron numerically with the parameters summarized in Table 1 below. The numerical code, as well as further details of the simulation go beyond the possibilities of the present application, and thus, will be published in further scientific papers.

Table 1. Summary of the simulation parameters.

parameter	value
wavelength (λ_l) of the THz pulses	600 μm
peak electric field strength (E_0) of the THz pulses	10 MV/cm
size of beam waist (w)	100-300 μm
carrier-envelope phase of the THz pulses	1.54 rad
profile type of the pulses	Gaussian
initial energy (E_{kin}) of the electrons in the bunch	0-60 keV

[0031] Table 2 below summarizes the electron energies E attainable for pairs of THz pulses with various beam waists and peak electric field strengths, as well as electrons with various initial energies used in the simulation studies. The data in Table 2 clearly show that kinetic energy of the electrons generated with an initial energy that falls in the range

0-60 keV can be significantly increased by means of the electron acceleration scheme according to the present invention.

Table 2. Electron energies attainable by the acceleration scheme of the invention.

λ_l	E_0	w	E_{kin}	Energy (E)
600 μm	10 MV/cm	300 μm	0 keV	59 keV
600 μm	10 MV/cm	600 μm	0 keV	50 keV
600 μm	20 MV/cm	300 μm	0 keV	240 keV
600 μm	20 MV/cm	600 μm	0 keV	191 keV
600 μm	10 MV/cm	300 μm	20 keV	144 keV
600 μm	10 MV/cm	600 μm	20 keV	126 keV
600 μm	20 MV/cm	300 μm	20 keV	360 keV
600 μm	20 MV/cm	600 μm	20 keV	301 keV
600 μm	10 MV/cm	300 μm	60 keV	223 keV
600 μm	10 MV/cm	600 μm	60 keV	200 keV
600 μm	20 MV/cm	300 μm	60 keV	455 keV
600 μm	20 MV/cm	600 μm	60 keV	392 keV

[0032] Instead of a single pair of THz pulses, the electron acceleration can also be realized at the actual spatial location of the bunch 40 of electrons by two, three or even four pairs of THz pulses, that is, by means of four, six or eight individual THz pulses that pair-wise travel essentially opposite to one another. In particular, Figure 1B illustrates a setup 100' with four pairs of THz pulses 10, 20; 11, 21; 12, 22; 13, 23 applied, wherein each pair arrives at the actual spatial location of the bunch 40 of electrons from a different direction; preferably, said directions are located around the propagation path 30, taken as an axis, of the electron bunch 40 inn about equal angular distances relative to one another, although, this is not necessary. An advantage of the application of more than one pairs of THz pulses at a time is that the overall peak electric field strength (E_0) of the resultant pulse used to accelerate the electrons can be arbitrarily increased by increasing the number of THz pulses to be applied.

[0033] If further pairs of THz pulses are focused on the already accelerated electrons at one or more further spatial locations - in the propagation path 30, in the direction of propagation of the bunch 40 of electrons - after the setup 100, 100' illustrated in Figure 1, the electron acceleration scheme according to the present invention becomes also suitable for the post-acceleration of electrons that have already been accelerated. Thereby, a multi-stage acceleration setup can be constructed. Figure 4A is a schematic representation of a possible exemplary embodiment of a setup 100" to accomplish multi-stage post-acceleration, wherein the bunch 40 of electrons accelerated by the first pair of THz pulses 10, 20 is accelerated further in the setup 100" along its propagation path 30 by means of a further pair of THz pulses 60, thereby implementing a post-acceleration of the bunch 40 of electrons in a second stage. Then, said bunch 40 of electrons can be subjected to a yet further post-acceleration at a further spatial location along its propagation path 30 by means of a third pair of THz pulses 70. It is immediately apparent to a person skilled in the art that the electron bunch 40 can be subjected to practically any number of post-accelerations along its propagation path 30, as far as the THz generation and synchronization discussed with reference to Figure 2A can be maintained for the increased number of pulse pairs.

[0034] A possible exemplary embodiment of the electron acceleration scheme according to the invention is shown in Figure 4B which is a schematic representation of a setup 100a", with synchronization, to implement multi-stage acceleration. Similarly to the setup 100a (see Figure 3) for single stage acceleration, here a laser pulse 90a generated by a high-energy laser 90 (1-5000 mJ) being also capable of handling the task of synchronization, is directed through a beam splitter 89, by means of which the beam of the laser pulse 89a is divided in two parts, in particular, to a first beam 90a1 and a second beam 90a2. The first beam (pulse) 90a1 is then led to the source 17 of electrons and is used to generate the bunch 40 of electrons. The second beam (pulse) 90a2 is directed through a further second beam splitter 88, by means of which it is divided again in two parts, namely to a first beam 90a21 and a second beam 90a22. Now, in the paths of the thus obtained beams 90a21 and 90a22, third beam splitters 85 and 87 are arranged, one in each path, thereby dividing each beam 90a21, 90a22 in two parts again, namely into beams (pulses) 90a211, 90a212 and 90a221, 90a222, respectively. The THz pulses 10, 20 required for the first-stage acceleration are generated by two pulses (here the pulses 90a211 and 90a221) from the thus obtained four pulses through optical means (source of THz pulses) 15, 25 configured to perform processes suitable for creating THz pulses, such as e.g. THz generation based on the tilted-front-pulse excitation technique (see above). The remaining two beams 90a212, 90a222 produced by the third beam splitters 85, 87, respectively, are directed through yet further fourth beam splitters 84, 86, respectively, by means of which the two beams 90a212, 90a222 are divided in two-two parts again, namely into further beams (pulses) 90a2221, 90a2222 and beams (pulses) 90a2121, 90a2122. From the thus obtained four pulses two pulses (here the pulses 90a2121 and 90a2221), similarly to the first-stage acceleration, through optical means 15', 25' configured to perform processes suitable for creating THz pulses, and in a synchronized manner, are used to generate the pair of THz pulses 60 required for the second-stage acceleration. Furthermore, the remaining two pulses, here the pulses 90a2122, 90a2222, similarly to the first- and second-stage acceleration, through optical means 15", 25" configured to perform processes suitable for creating THz pulses, and in a synchronized manner, are used to generate the pair of THz pulses 70 required for the third-stage acceleration.

[0035] To accomplish synchronization in the post-acceleration stages, variability of the optical path lengths of the THz pulses 60, 70 of the pulse pairs generated by the beams 90a2221, 90a2222, 90a2121, 90a2122 is also exploited besides choosing/adjusting the optical path lengths of said beams as discussed above. In particular, in the path of each THz pulse 60, 70 of the pulse pairs, an optical element 65, 66 and 67, 68 is arranged, wherein each of said optical elements preferably has got a rectangular shape and is made of a material with non-linear optical properties, in particular, of lithium niobate crystal, in such a way that a side surface of each optical element 65, 66; 67, 68 parallel to the direction of propagation of the THz pulses 60, 70 travelling opposite to one another contains the optical axis of the THz pulses 60, 70 (see Figure 4B). In this way, half of each THz pulse 60, 70 along a direction transversal to the direction of propagation of the THz pulses 60, 70 propagates within the respective optical element 65, 66; 67, 68 of given thickness, while the remaining half of each pulse 60, 70 propagates in vacuum. Within the optical elements 65, 66; 67, 68, each half of the pulses 60, 70 travels with a velocity that is smaller than the propagation velocity in vacuum. Hence, those halves of the THz pulses 60, 70 which travel through the material of the optical elements will reach the propagation path 30 of the bunch 40 of electrons located at halfway between the optical elements 65, 66 in the second acceleration stage and at halfway between the optical elements 67, 68 in the third acceleration stage at a later time compared to those halves which travel in vacuum. The amount of time delay between said halves of the THz pulses 60, 70 can be adjusted by the lengths of the paths run by the respective half pulses within the optical elements 65, 66; 67, 68, in particular, by the thickness of each optical element 65, 66; 67, 68 along the propagation path of said pulses 60, 70 - in knowledge of the parameters of a setup to be used for the acceleration, the optical path lengths required to achieve the desired synchronization can be determined in a manner known by a skilled person in the art (e.g. by preliminary calculations). In the second acceleration stage, when travelling along the propagation path 30 the bunch 40 of electrons passes between the optical elements 65, 66 (where the electric field strength of the resultant pulse produced by the THz pulses 60 changes from positive to negative value, i.e. it is practically 0 MV/cm, at the instant of time when said bunch 40 arrives). Said bunch 40 then reaches the end of the optical elements 65, 65 along the propagation path 30 in the direction of propagation, to where - with proper synchronization - those portions of the THz pulses 60 arrive as well that are responsible for acceleration. The bunch 40 of electrons interacts with the resultant pulse arising due to superimposition of the THz pulses 60, or rather the accelerating electric field strength of said resultant pulse. As a result of the interaction, the electrons in the bunch 40 gain energy and get accelerated. Then, in the third acceleration stage, the bunch 40 of electrons passes between the optical elements 67, 68 (where the electric field strength of the resultant pulse produced by the THz pulses 70 changes from positive to negative value, i.e. it is practically 0 MV/cm, at the instant of time when said bunch 40 arrives). Said bunch 40 then reaches the end of the optical elements 67, 68 along the propagation path 30 in the direction of propagation, to where - with proper synchronization - those portions of the THz pulses 70 arrive as well that are responsible for acceleration. The bunch 40 of electrons interacts with the resultant pulse arising due to superimposition of the THz pulses 70, or rather the accelerating electric field strength of said resultant pulse. As a result of the interaction, the electrons in the bunch 40 gain energy again and get accelerated further. It is noted that the setup 100a" of Figure 4B can also be used if the other halves of the THz pulses 60, 70 are delayed (i.e. when first halves of the THz pulses 60, 70 in the direction of propagation of said pulses performs acceleration). It is also noted here that the bunch 40 of electrons can be accelerated in the discussed exemplary setup until the electrons in the bunch 40 interact with the accelerating portions of the spatially separated two resultant pulses each obtained by superimposition of the THz pulses 60, 70. This holds until the electric field strengths of said resultant pulses are negative; the largest extent of acceleration of the bunch 40 of electrons is achieved if the interaction starts to operate between the bunch 40 and the electric field of each resultant pulse at the instant when the electric field strength of respective said resultant pulse changes from positive values to negative ones.

[0036] The energy of the accelerated electrons can be increased almost linearly in the multi-stage post-acceleration scheme according to the invention. The results of our calculations performed for the multi-stage acceleration setup shown in Figure 4B are summarized in Figure 5. The calculations were performed with four different initial electron energies (0, 20, 40, and 60 keV) and at three different THz pulse frequencies. According to the calculations, if a single pair of THz pulses is used for the acceleration in each stage, wherein each THz pulse has the energy of 225 μJ and the frequency of 0.5 THz (i.e. its wavelength is 600 μm), initially standing electrons can be accelerated to the energy of 0.5

MeV, while electrons with the initial energy of 60 keV are accelerated to the energy of about 0.7 MeV in three separate stages. In the case of applying THz pulses of the same energy for the acceleration, the THz pulses of larger frequency induce higher accelerations, and at the frequency of 3 THz, electrons with the energy of about 2 MeV can also be produced.

[0037] It is here noted that, along with optimizing the acceleration parameters further, electrons having initial energies higher than those shown in Figure 5 (up to 10 MeV) can also be accelerated by means of the above discussed multi-stage post-acceleration scheme.

[0038] Furthermore, in our studies we have come to the conclusion that the acceleration of electrons/bunch of electrons can be accomplished in such cases as well, wherein - in specific geometry - the THz pulses 10, 20 do not travel opposite to one another, but their directions of propagation form a given angle 33 with the propagation path 30, as axis, of the electrons. In such a configuration, the requisite for the acceleration is that the directions of propagation of the THz pulses 10, 20 and the propagation path 30 of the bunch 40 of electrons to be accelerated lie in a single common plane (in Figure 6, e.g. in the xz plane) and the two THz pulses 10, 20 travel symmetrically with respect to a plane defined by the propagation path 30 of the bunch 40 of electrons (that is, in Figure 6, the yz plane). A possible exemplary setup 100"' to implement this angled electron acceleration is illustrated schematically in Figure 6. A proper synchronization of the THz pulses 10, 20 to the bunch 40 of electrons required in order that the acceleration take place can be achieved by e.g. the setup 100a shown in Figure 3, and hence it is not discussed here in more detail.

[0039] It is here noted that the direction of propagation of the bunch 40 of electrons that has already been accelerated as discussed above can be changed if required - as is apparent to a skilled person in the art. As it is shown in Figure 6, changing the direction of propagation can be performed by e.g. inserting a static magnetic field 35 into the propagation path 30 of said bunch 40 of electrons.

[0040] It is here also noted that the electron acceleration scheme according to the present invention can also be realized with the application of multi-cycle pulses (i.e. with THz pulses containing preferably more than two optical cycles). When such pulses are applied - similarly to the single-cycle case - the accelerating portion of the electric field strength of the first cycle accelerates the electron(s), while the deceleration portion thereof decelerates the electron(s). Due to the acceleration, the velocity of the electron(s) increases, and thus, the electron(s) leaves/leave the field of the resultant pulse created by the THz pulses; that is, the electron(s) will not sense further optical cycles of the incoming THz pulses. Hence, it may be stated that if multi-cycle THz pulses are used for the acceleration, the bunch of electrons can attain basically the same extent of energy gain than in the case wherein single-cycle THz pulses are applied.

[0041] In light of the above, relativistic electrons/bunches of electrons with the energy of even several hundreds of keV can be produced by the proposed scheme when applying THz pulses.

[0042] The electron acceleration scheme according to the present invention can be applied highly preferably in free electron lasers and electron post-accelerators as the initial relativistic electron source to replace traditional electron guns and linear accelerators. The electron acceleration scheme according to the present invention can be used highly preferably to accelerate ultrashort relativistic electron bunches, in particular of sub-picosecond (sub-ps) length/duration, to energies falling in the range of several eV to 100 keV and to post-accelerate electrons with the energy of even 10 MeV or smaller. Furthermore, time-resolved electron microscopy and electron diffraction offer yet further fields of application for the present invention. A great advantage of the present invention over the traditional electron sources is that both its implementation and maintenance costs are much less than the similar costs that arise in the case of traditional electron sources. Furthermore, its dimensions are also smaller than those of the traditional electron sources. Consequently, the spread of the usage of relativistic electrons in various fields (e.g. material testings, medical science) can be significantly enhanced by means of the electron acceleration scheme according to the invention.

Claims

1. A method to accelerate electrons to relativistic energies, comprising the steps of generating, by an electron source (17), electrons (40) of low initial energy;
providing, at the location of the electrons, at least two THz pulses (10, 20; 60, 70) synchronized to an instant of time of the electron generation;
generating, at the location of the electrons, a non-steady resultant electric field by superimposing electric fields of the at least two THz pulses;
making the electrons to interact with the resultant electric field accordant to a temporal evolution of the electric field strengths of the THz pulses, thereby increasing electron energy, and thus, accelerating the electrons along a propagation path (30), wherein
synchronizing the provision of the THz pulses and the instant of time of the electron generation to one another takes place by providing, at the location of the electrons at the instant of time of the electron generation, each of the THz pulses as a THz pulse with an electric field of predetermined phase, said phase being the same for each THz pulse, and by generating the non-steady resultant electric field as an electric field with an electric field strength having a

direction that represents an accelerating influence on the electrons.

2. The method according to claim 1, wherein the same phase of the at least two THz pulses are adjusted in such a way that the electric field strength of each THz pulse changes from positive values to negatives values at the instant of time of the electron generation at the location of the electrons.

3. The method according to claim 1 or 2, wherein to decrease spatial dimension of the resultant electric field, the at least two THz pulses are focused on a region with predetermined dimension, thereby decreasing, at the location of the electrons and accordant to the temporal evolution of the electric field strengths of the THz pulses, decelerating influence on the electrons of said non-steady resultant electric field.

4. The method according to claim 3, wherein focusing the at least two THz pulses is performed on a region with a dimension in the same order of magnitude as the wavelength of the THz pulses, preferably on a region with a dimension equal to said wavelength.

5. The method according to any of claims 1 to 4, wherein the at least two THz pulses are provided at the location of the electrons by pairs of THz pulses travelling essentially opposite to one another and transversely to the propagation path of the electrons, wherein the number of the pairs ranges preferably from one to four.

6. The method according to any of claims 1 to 4, wherein the at least two THz pulses are provided, at the location of the electrons, by THz pulses each having an optical axis, wherein said optical axes are in a plane containing the propagation path of the electrons and form an angle with one another in said plane that ranges from at least 60° to at most 180°.

7. The method according to any of claims 1 to 6, wherein generating the electrons and providing the THz pulses are performed by pulses, preferably by laser pulses, of the same source (90), and synchronizing to the instant of time of the electron generation is performed by setting under pre-determined conditions an optical path to be travelled by the pulses applied to generate the THz pulses.

8. The method according to any of claims 1 to 7, further comprising
providing, at a further location of the electrons along the propagation path (3) thereof, at least a further pair of THz pulses (60) synchronized to the instant of time of the electron generation; generating, at said further location of the electrons, a further non-steady resultant electric field by superimposing electric fields of the at least two further THz pulses (60); making the electrons to interact with said further resultant electric field accordant to the temporal evolution of the electric field strengths of said further THz pulses, thereby increasing the electron energy further by the interaction, and thus, subjecting said electrons (40) to post-acceleration, wherein
synchronizing the provision of the further THz pulses (60) and the instant of time of the electron generation to one another takes place by providing, at the further location of the electrons at the instant of time of the electron generation, each of the further THz pulses as a THz pulse (60) with an electric field of predetermined phase, said phase being the same for each further THz pulse, and by generating the further non-steady resultant electric field as an electric field with an electric field strength having a direction that represents an accelerating influence on the electrons, and adjusting each optical path travelled by half of each THz pulse after the THz pulses have been generated and before the superimposition of the electric fields of the THz pulses takes place to an extent required in order to synchronize the resultant electric field generated at the actual location of the electrons to the electrons, wherein half of a THz pulse is considered in an extension of the respective THz pulse transversal to the propagation direction of the THz pulse.

9. The method according to claim 8, wherein the electrons (40) are post-accelerated in several stages by performing the steps of the method at several locations of the propagation path (30) of the electrons through applying at least two further THz pulses (70) at those locations.

10. The method according to any of claims 1 to 9, wherein the THz pulses are provided by THz pulses containing between one and two optical cycles, preferably about one and a half optical cycle, and more preferably a single optical cycle.

11. The method according to any of claims 1 to 10, wherein the THz pulses have peak electric field strengths in the range 0.05-500 MV/cm.

12. The method according to any of claims 1 to 11, wherein the electrons are produced by using one of a gas jet, electron gun, emission from a metal layer as the electron source (17).

13. The method according to claim 12, wherein the initial energy of the electrons (40), depending on the type of the electron source (17) used, is essentially in the range 0-10 MeV, preferably ranges from essentially 0 eV to at most about 100 keV, and more preferably ranges from several eV to about 60 keV.

14. The method according to any of claims 1 to 13, wherein the electrons form bunches of electrons with charge densities ranging from 10^3 nC/cm^3 to 10^{11} nC/cm^3.

15. A setup (100a) to accelerate electrons to relativistic energies, comprising

- an electron source (17) configured to generate electrons (40) of low initial energy at an instant of time at a location, the electrons, after the generation, propagate along a propagation path (30);
- a THz pulse source (15, 25) configured to generate simultaneously pairs of THz pulses (10, 20) and to provide said pairs of THz pulses at the location of the electrons at the instant of time of the electron generation; said THz pulses generate a non-steady resultant electric field at the location of the electrons by superimposing electric fields of the THz pulses; wherein

the electron source (17) and the THz pulse source (15, 25) are configured to operate in a synchronized manner, wherein at the location of the electrons at the instant of time of the electron generation the electric field strength of each THz pulse (10, 20) is of pre-determined phase, said phase being the same for each THz pulse, and the non-steady resultant electric field is provided by an electric field with an electric field strength having a direction that represents an accelerating influence on the electrons (40).

16. The setup according to claim 15, further comprising a unit (90) adapted to perform synchronization, said unit (90) being optically operatively coupled to both the electron source and the THz pulse source, wherein the optically operative coupling comprises a first optical path with a first length, said first optical path extending from said unit to the electron source, and a second optical path with a second length, said second optical path extending from said unit to the THz pulse source, and wherein the first length and the second length are chosen so as to ensure synchronized operation of the electron source and the THz pulse source by said unit.

17. The setup according to claim 16, wherein the unit (90) is provided by a laser source configured to emit a laser pulse, said laser pulse being adapted to form the operative coupling upon its passing over the first and second optical paths.

18. The setup according to claim 17, further comprising a first beam splitter element (89) to divide the laser pulse in two laser beams (90a1, 90a2), and arranged to feed the laser beams obtained by splitting into the first and second optical paths.

19. The setup according to claim 18, further comprising a second beam splitter element (88) to divide one of the laser beams (90a1, 90a2) produced by the first beam splitter element (89) in further two laser beams, and arranged to feed the further two laser beams obtained by splitting into two branches of the second optical path created by said second beam splitter element (88).

20. The setup according to claim 19, wherein the electron source is provided by one of a gas jet, electron gun and metal layer operated to emit electron by one of the laser beams obtained through splitting by the first beam splitter element, and the THz pulse source is provided by at least two optical units, each configured to perform THz generation by means of using independently the laser beams produced by the second beam splitter element from the other laser beam obtained through splitting by the first beam splitter element, said units being arranged symmetrically with respect to the propagation path of the electrons.

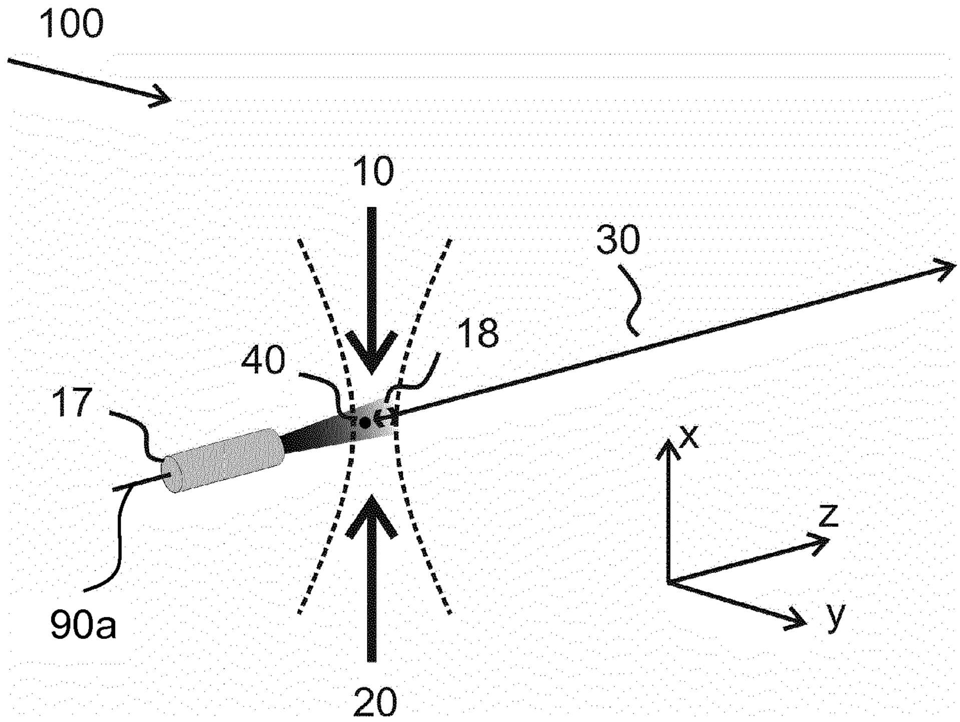

Figure 1A

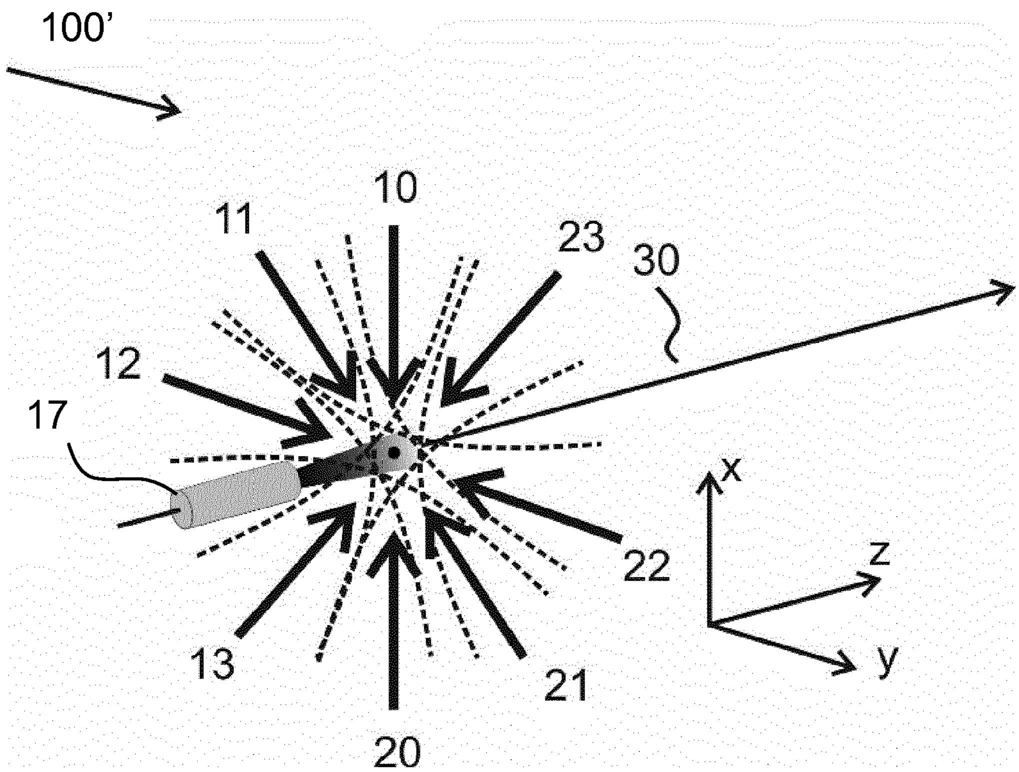

Figure 1B

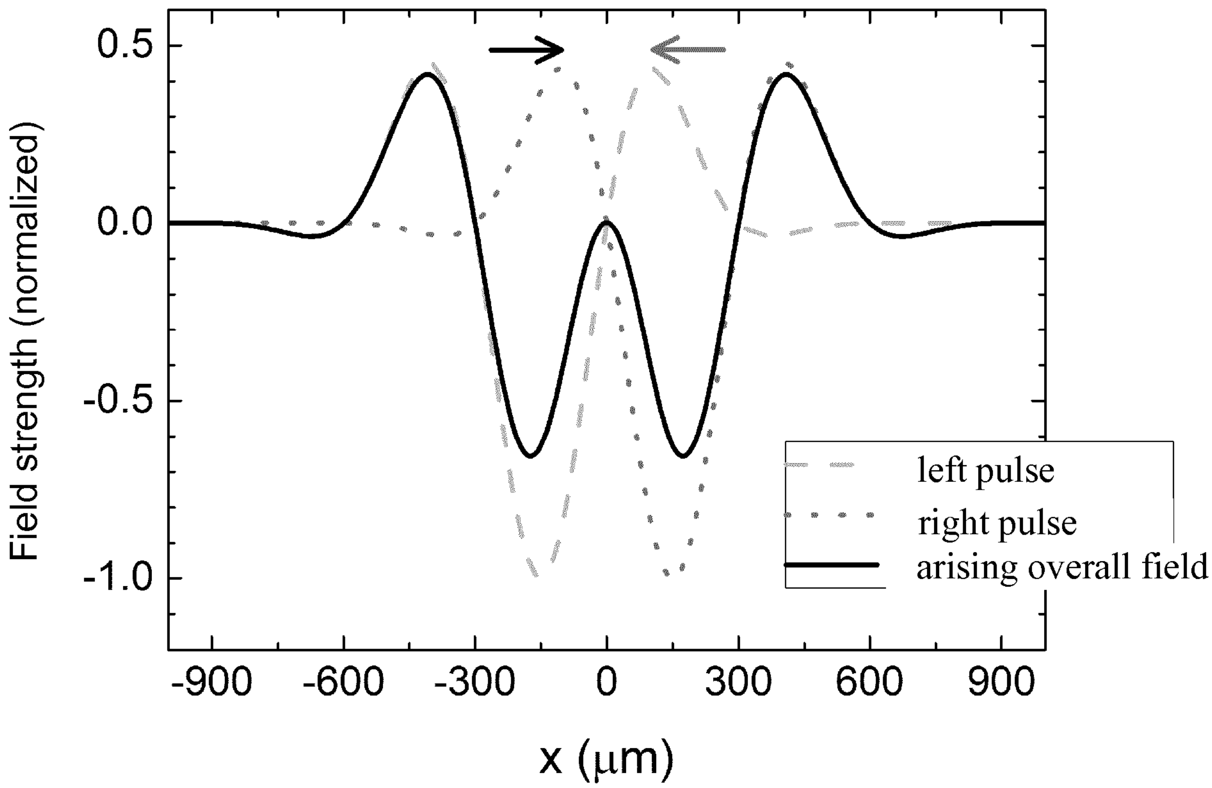

Figure 2A

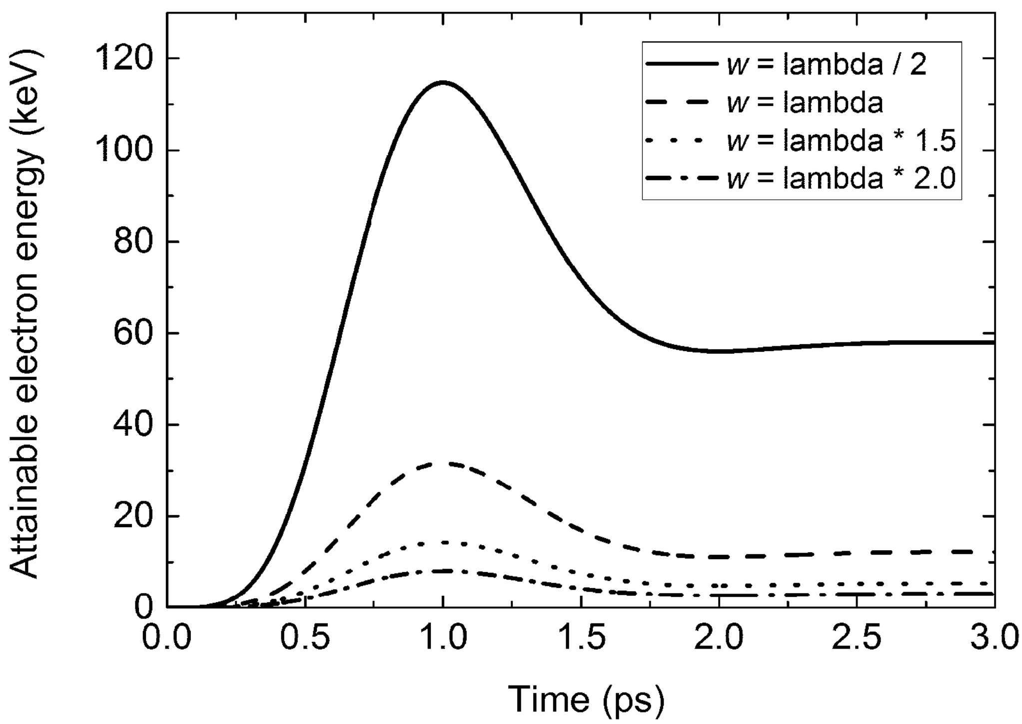

Figure 2B

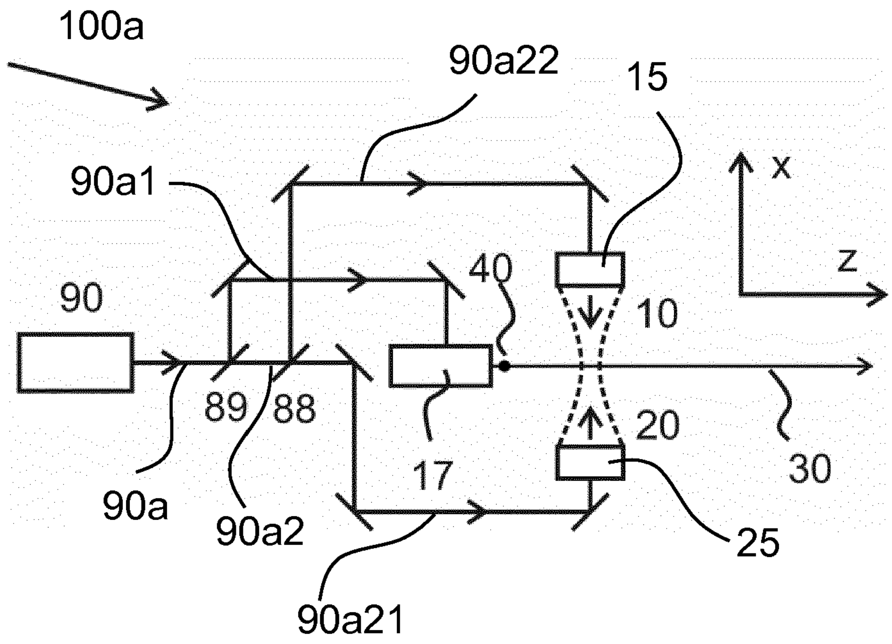

Figure 3

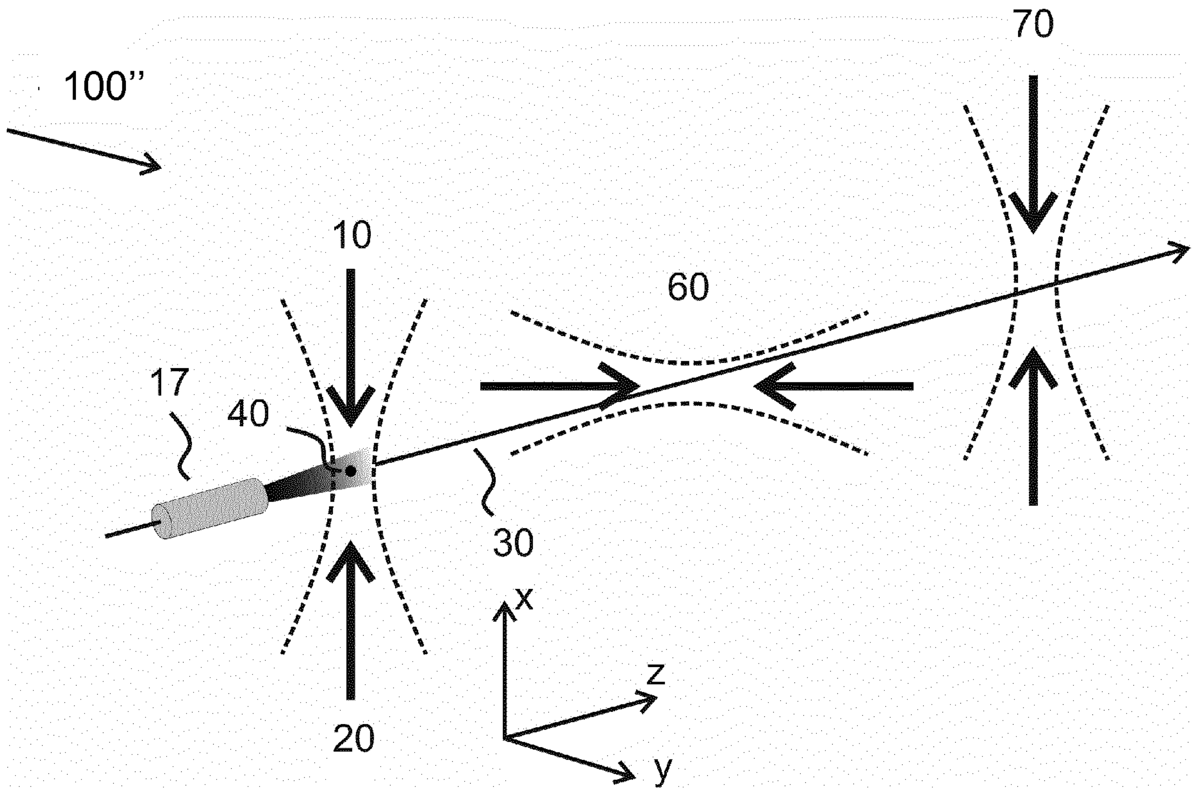

Figure 4A

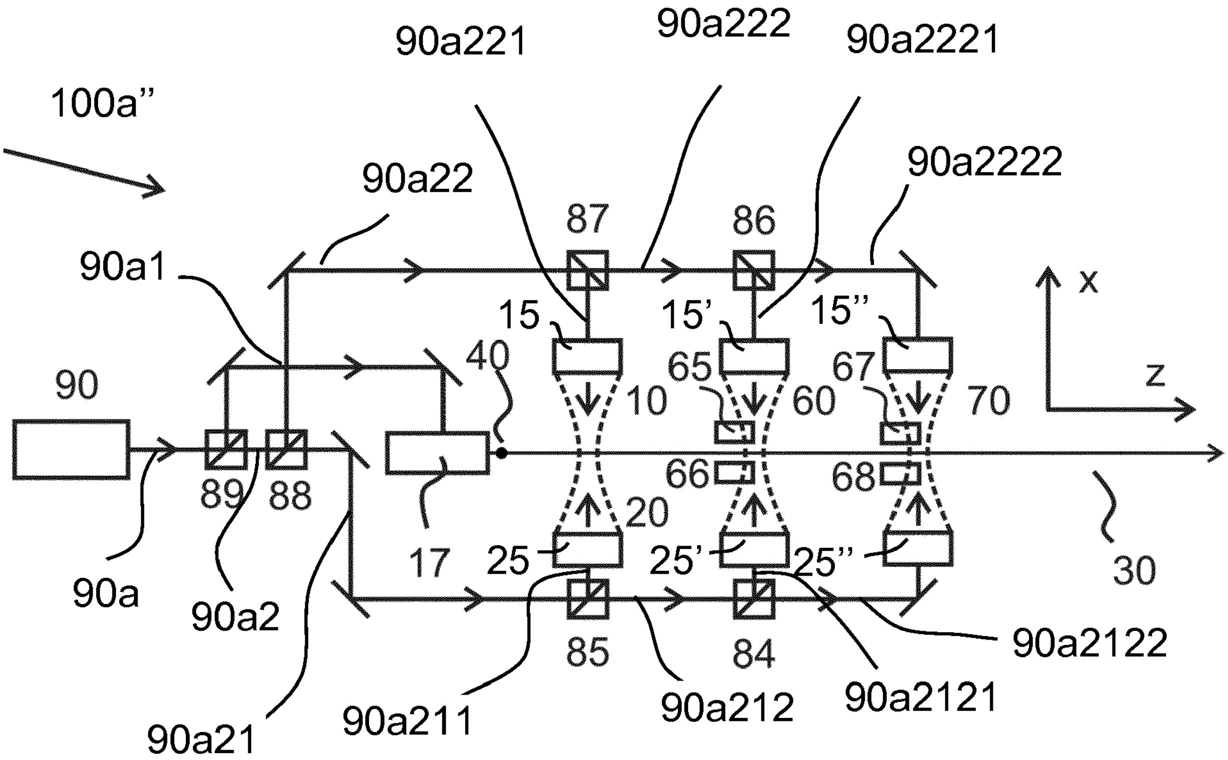

Figure 4B

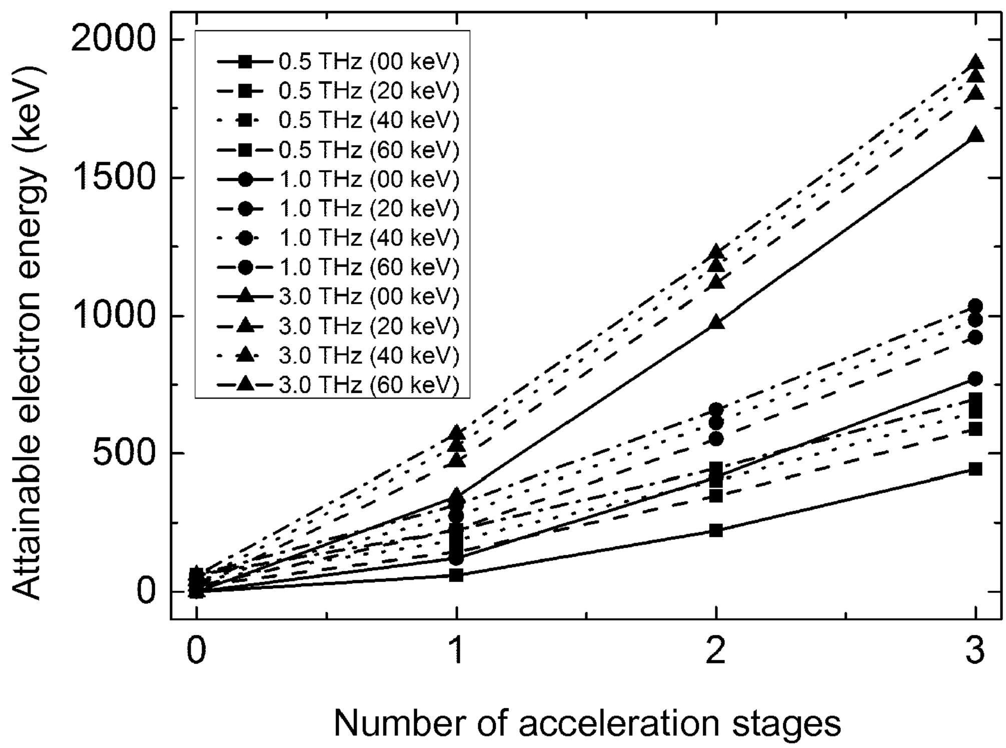

Figure 5

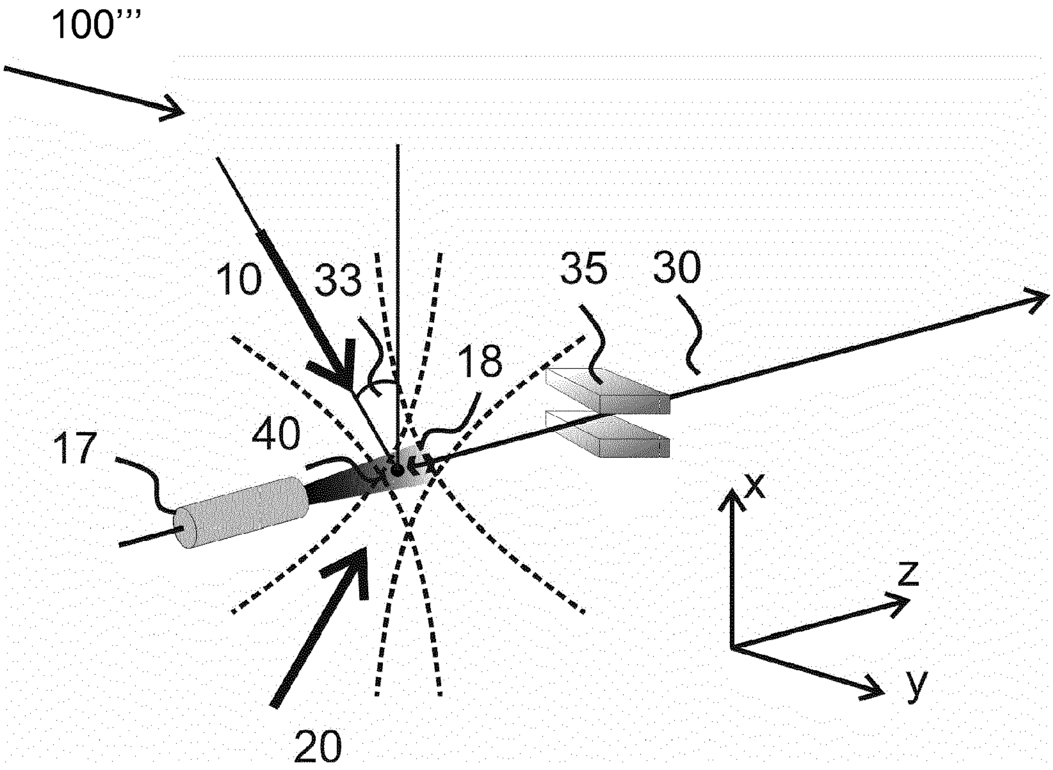

Figure 6

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EUROPEAN SEARCH REPORT

Application Number
EP 18 16 6187

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The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
The Hague	6 March 2019	Clemente, Gianluigi

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EUROPEAN SEARCH REPORT

Application Number
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page 2 of 2

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