United States Patent

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[72] Inventors **Yasutsugu Takeda**
Tokyo;
Isao Matsui, Kokubunji-shi, both of Japan

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[73] Assignee **Hitachi, Ltd.**
Tokyo-to, Japan
[32] Priority **Mar. 12, 1967**
[33] **Japan**
[31] **42/29795**

[54] **CHARGED PARTICLE ACCELERATOR**
15 Claims, 11 Drawing Figs.

[52] **U.S. Cl.** **315/4,** 331/94.5, 328/233
[51] **Int. Cl.** **H05h 5/00**
[50] **Field of Search** 331/94.5; 315/4; 328/33, 233

[56] **References Cited**

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3,267,383 8/1966 Lohmann 328/33

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Toraldo Di Francia, " Interaction of Focused Laser Radiation with a Beam of Charged Particles" Nuovo Cimento 37(4) 16 June 1965. pp. 1553– 1560.

Primary Examiner—Ronald L. Wibert
Assistant Examiner—R. J. Webster
Attorneys—Paul M. Craig, Jr., Donald R. Antonelli and Craig, Antonelli and Hill

ABSTRACT: A device, in which light waves are directed to the surface of a periodic structure constituted of a material having high reflectivity of the light wave used, whereby a field having a periodic strength of an electric field vector of the light wave is generated in the vicinity of the surface of said periodic structure, and the energy of the light wave is supplied to the charged particles while said charged particles pass through said field, thereby accelerating the charged particles.

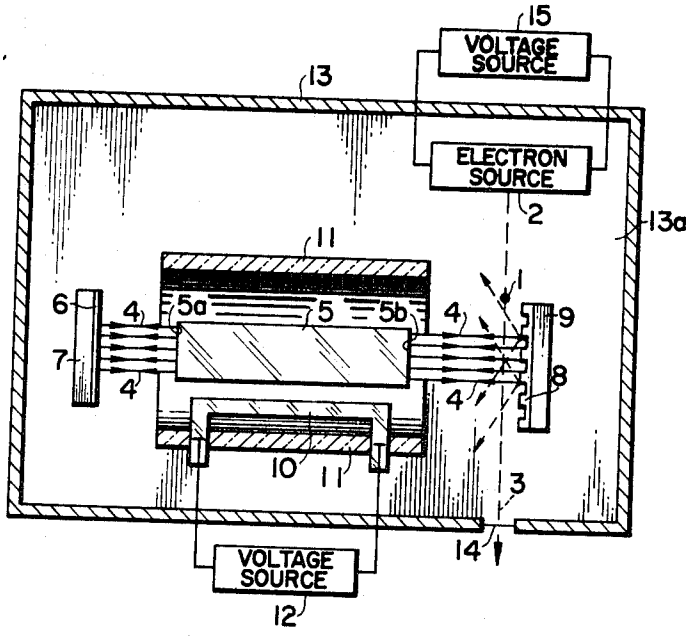


FIG. 1

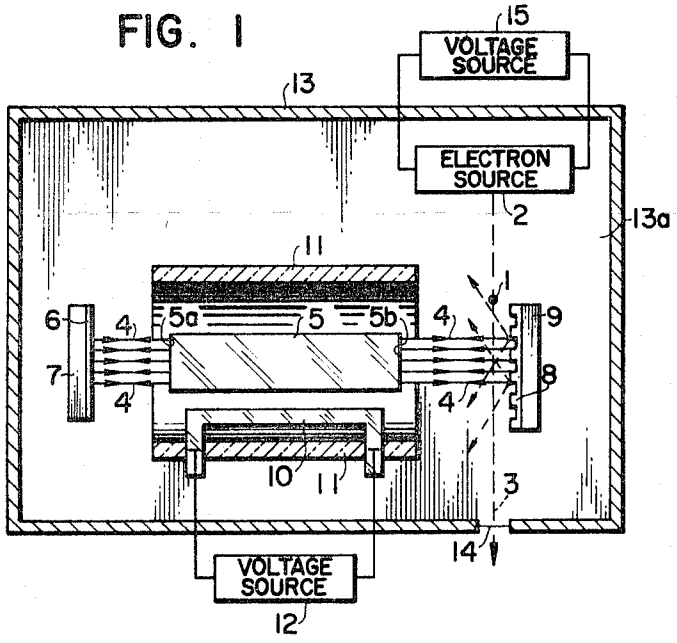


FIG. 3

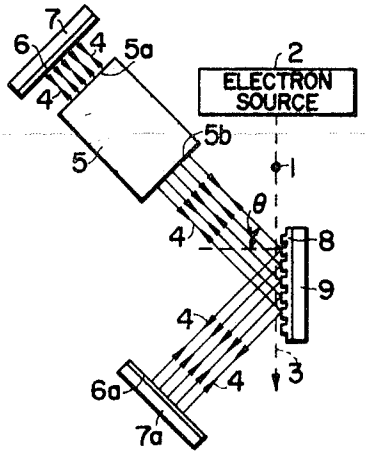


FIG. 2

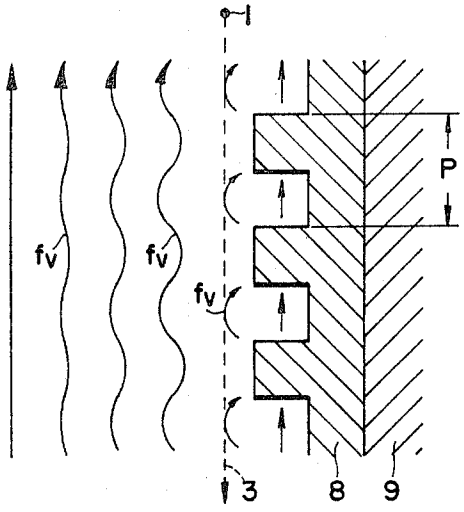


FIG. 4a

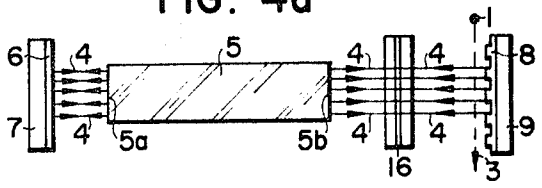
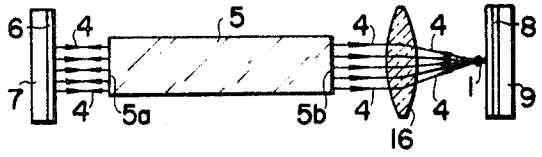


FIG. 4b



INVENTORS

YASUTSUGU TAKEDA & ISAO MATSUI

BY Craig & Antonelli

ATTORNEYS

FIG. 5a

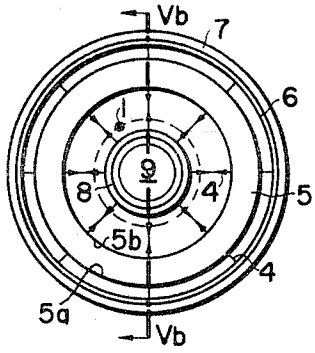


FIG. 5b

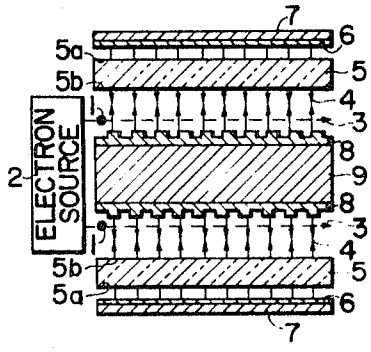


FIG. 6

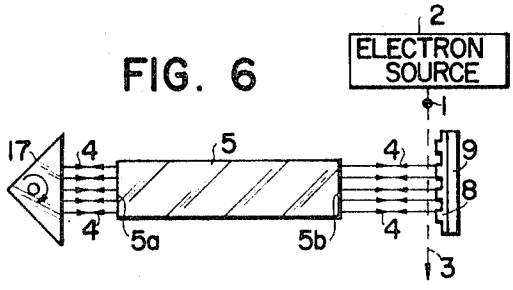


FIG. 7

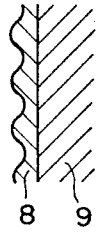


FIG. 8

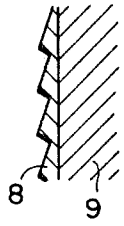
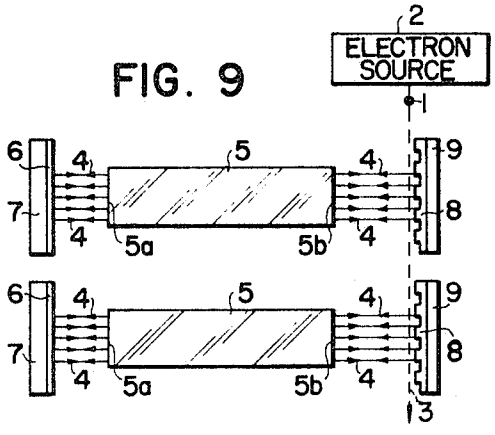


FIG. 9



INVENTORS

YASUTSUGU TAKEDA & ISAO MATSUI

BY Craig & Antonelli

ATTORNEYS

CHARGED PARTICLE ACCELERATOR

This invention relates to electro-optical devices, and more particularly to a charged particle accelerator in which input energy is converted into coherent light wave energy, such as ultraviolet rays, visible light or infrared rays, and the resultant converted energy is then transferred to charged particles, thereby accelerating the particles.

Conventionally, the means for converting input energy into a coherent light wave may be provided in the form of a laser device. In addition, there is a known arrangement, as disclosed in U.S. Pat. No. 3,267,383, in which the light wave energy produced by a laser device is supplied to charged particles. Specifically, first and second periodically transparent structures, each of which has a planar surface, are juxtaposed to within several wavelengths of the light. A coherent light is directed through the periodic structures, and the changed particles are directed therebetween, whereby an evanescent wave is generated between the periodic structures, thereby accelerating the charged particles.

In the device disclosed in the aforementioned U.S. Patent the periodic structures must be transparent to the light wave used since it is required that the light wave pass through the structures to interact with the charged particles propagated therebetween. Thus, the periodic structures in this known arrangement cannot be made of a nontransparent material having high reflectivity, such as metal, due to the particular construction of the arrangement. However, it has been noted that charge deposits on the surface of the periodic structures have a tendency to form and these charge deposits act to interfere with and distort the path of the charged particles resulting in a discharge phenomenon. For this reason, materials having a good electrical conductivity, such as metal, could be used very advantageously for the periodic structures, if it were not for the previously mentioned conflicting requirement of transparency.

When the coherent light is directed through low-transparent periodic structures, the evanescent light generated between the periodic structures is attenuated, so that the power efficiency of the light energy is considerably lowered. In addition, it is desirable to arrange the two mutually facing plates forming the periodic structures to be as accurate as possible from the standpoint of parallelism, distance between the two periodic structures and mutual arrangement between the grooves providing the first and second periodic structures. However, it is hardly possible to arrange precisely the two periodic structures when the light wave used becomes as short as the wavelength of visible light or ultraviolet rays.

An object of this invention is to provide a charged particle accelerator, in which input energy is converted into light wave energy, and the resultant energy is further converted directly into the energy by which the charged particles are accelerated.

Another object of this invention is to provide a charged particle accelerator, in which the light waves whose wavelengths widely range from the infrared ray region to the ultraviolet ray region are used, thereby accelerating the charged particles.

Still another object of this invention is to provide a markedly compact charged particle accelerator, comprising a device for producing or reinforcing the light wave energy, and a device for directly effectuating acceleration of the charged particles.

A further object of this invention is to provide a charged particle accelerator of the type described, wherein the space at which the light wave energy is spatially stored to a maximum is overlapped by the space corresponding to the path of the charged particles, thereby realizing efficient acceleration of the charged particles.

A still further object of this invention is to provide a charged particle accelerator, in which the path length of the charged particles can be made distinctively shorter than that of the conventional accelerator.

An additional object of the invention is to provide a charged particle accelerator capable of removing undesirable charging

phenomenon in the vicinity of the path of the charged particles.

To achieve the said objects, the device of this invention comprises a periodic structure providing a plurality of grooves and constituted of a material with relatively high reflectivity, means for directing light waves to said periodic structure, and a means for injecting the charged particles along a path adjacent the surface of said periodic structure, whereby a field having a periodic strength of the electric field vector of the light wave is generated in the vicinity of the surface of the periodic structure, thereby accelerating the charged particles.

The above mentioned objects and other objects with the advantages thereof can be clearly discerned from the following detailed description of this invention which has been illustrated in the accompanying drawings.

FIG. **1** is a schematic diagram of an embodiment of this invention;

FIG. **2** is a diagram showing an electric field vector of light wave;

FIG. **3** is a schematic diagram showing the essential part of another embodiment of this invention;

FIGS. **4***a* and **4***b* are schematic diagrams showing the essential parts of still another embodiment of this invention, FIG. **4***a* providing a plane view, and FIG. **4***b* providing a front view thereof.

FIG. **5***a* is a schematic diagram showing the essential part of another embodiment of this invention;

FIG. **5***b* is a sectional view taken along line V^0—V_b in FIG. **5***a*;

FIGS. **6** and **9** are schematic diagrams showing the essential parts of other embodiments of this invention; and

FIGS. **7** and **8** are sectional views showing the periodic structures of other embodiments according to this invention.

The charged particles to be accelerated according to this invention include electrons, various ions, protons, positrons, and so forth. However, for simplicity of explanation, the embodiments presented in this specification will be related only to the acceleration of electrons.

Now referring to FIG. **1**, the reference numeral **1** designates an electron particle derived from an electron source **2** and traveling along an electron path **3**. A coherent light wave **4** is generated in laser material **5**, being provided with end faces **5***a* and **5***b*. A highly reflective film **6** with respect to the light wave **4** is provided on a base plate **7** supporting the highly reflective film **6** opposite the end face **5***a*, and a periodic structure **8** made of a material with high reflectivity to the light wave **4**, such as gold or silver, is supported opposite end face **5***b* by a base plate **9**. The periodic structure **8** is formed, for example, by disposing a plurality of parallel grooves on the surface of a metal plate. A flash tube **10** is positioned adjacent laser material **5** within a cylindrical reflection mirror **11**, a power source **12** being connected to the flash tube. A vacuum tight vessel **13** enclosing the elements of the system is provided with a window **14** for drawing out electrons, so that a vacuum space **13***a* is formed by the vessel **13** and window **14**. A power source **15** for the electron source **2** is also provided. All the components, excepting the flash tube power source **12** and the power source **15** for the electron source, are disposed in the vacuum space **13***a*. The aim of this particular arrangement is to prevent occurrence of unfavorable phenomena caused by collision of electron **1** or light wave **4** against molecules or ions in the atmosphere.

Being thus formed, the structure is operated in the following manner. The flash tube **10** is illuminated by the power supplied from the power source **12**. The sum of the illuminated energy (hereinafter referred to as flash tube output energy) serves as a main portion of the input energy to this device. From this standpoint, therefore, the flash tube output energy will hereafter be taken up in place of the input energy. Said flash tube output energy effectively excites the laser material **5** by the act of cylindrical reflection mirror **11**, in the known manner. The laser material **5** emits via its end faces **5***a* and **5***b* a light wave **4** whose wavelength λ is determined by the

material used. The light wave 4 from the end face 5*a* is directed to the highly reflective film 6 which is supported by the base plate 7. This light wave is then reflected at said reflective film 6, and the light wave thus reflected is directed back to the laser material 5 in which the excitation is promoted by the known induced radiation effect. This is called the positive feedback effect.

The light wave 4 emitted from the end faces 5*b* travels toward the periodic structure 8 which is supported by the base plate 9. This light wave is then reflected at said periodic structure 8. In general, the light wave injected perpendicular to the surface of the periodic structure 8 is reflected in multiple directions. Among these reflected light waves, the one returned toward the direction along which the light wave has been injected thereto is called a zero-order reflection light wave. In the device having a structure as described, this zero-order reflection light wave plays an important factor in the laser oscillation. The zero-order reflection light wave is directed to the laser material 5 again, to cause positive feedback action.

The device is so designed that the light wave reflected by the highly reflective film 6, which has been previously emitted from the end face 5*a* of the laser material 5, and the light wave of zero-order reflection from the periodic structure 8, which has been previously emitted from the end face 5*b* of the laser material 5, serve to strengthen each other therein. Thus, the highly reflective film 6 and the periodic structure 8 including the laser material 5 in the space therebetween serve as a optical resonator. Consequently, the optical resonator is filled with the energy of the light wave 4 to a most powerful level. It is to be noted that all the reflections at the periodic structure 8, excepting the zero-order reflection, are lost from the resonator. Such loss, however, may be minimized by returning the reflected light waves other than the zero-order reflection to the periodic structure by the use of a reflection mirror, in the known manner.

An electron 2 is emitted from the electron source 2, which has been activated by the power source 15, so as to travel along the path 3. At least a part of this electron path 3 intersects with the space filled with the energy of the light waves 4 or, in other words, a part of this path 3 is passed through the interior of the optical resonator so as to provide interaction with the light energy therein. The electron path should be positioned in parallel with the surface of the periodic structure 8 and perpendicular to the direction of the plural grooves disposed periodically on the surface of the periodic structure 8. The closer the path 3 is positioned to the surface of the periodic structure 8, the more effective will become the accelerating effect.

As will be specifically described later, the field having the periodic strength of the electric field vector of the light wave which has an accelerating effect on charged particles is produced at the area located within (about 10 wavelengths of the light wave used) from the surface of the periodic structure 8. Accordingly, the electron accelerating effect can be obtained within this area. The electron accelerated by the field of the electric field vector of the light wave passes through the electron window 14, and provides the output of this accelerator. Needless to say, this accelerator may be applicable to timewise continuous operation or pulse operation.

Referring to FIG. 2, the principle of the operation wherein the electron 1 is accelerated by the light wave 4 while said electron is passed through the space filled with the energy of the light wave 4, i.e., the space of the near periodic structure 8 in the optical resonator, will hereafter be explained.

In FIG. 2, an electron particle 1 travels along a path 3 adjacent the face of the periodic structure 8 mounted on the base plate 9, and f_V represents waves which indicate a distribution of the periodic strength of the electric field vector at a certain time, of the light wave produced in the vicinity of the periodic structure 8 in case a light wave 4 is directed to that structure. Specifically, the electric field vector of the laser field is produced in the direction perpendicular to the direction along which the light wave travels, as in the case of the electric field vector of a high-frequency field. Thus, by action of the periodic structure 8, there is periodically produced a strong portion and a weak portion in the amplitude of the electric field vector, in the vicinity of the surface of the periodic structure 8. In order to let the electron receive the accelerating effect, it is necessary that at least one of the components of the light wave electric field vector should have a field of the electric field vector of a light wave whose amplitude has the periodic variation determined by the cycle of the periodic structure 8. Accordingly, it is necessary to arrange for the direction of the light wave electric field vector to be parallel to the electron path 3.

The electron particle acceleration in the field of said electric field vector is done in the same manner as in the Alvarex-type linear accelerator, noted in "Iv. Ion Accelerators," page 366 to 368, Handbuch der Physik, Bank XLIV, Springer-Verlag, 1959. Now, in order to obtain a velocity matching between the laser field and the electron, it is necessary to satisfy the following equation, along the electron path.

$$n\lambda/c=p/v \quad (1)$$

where p: pitch of structure 8
v: velocity of electron
c: velocity of light
λ: wavelength of light
(note: n=1, 2, 3,—)

By selecting p, v, c and λ so that equation (1) is satisfied, the electron acceleration, if once started, is successively progressed with a behavior as in the known linear accelerator. As the velocity of the electron increases, it is necessary to gradually elongate the pitch P. On the other hand, when the velocity of the electron approaches the velocity of light as the result of acceleration, said electron velocity becomes early constant and only its mass is increased. Therefore, the portion of the periodic structure where it is necessary to provide a change in the pitch P so as to satisfy equation (1) need be only a small initial part of the whole of the periodic structure 8. This means that the periodic structure can be manufactured without particular considerations. Also, it is possible to eliminate the pitch by increasing the emitting speed of the electron from the electron source or by sufficiently increasing the amplitude value of the electric field vector of the light wave. To this end, the specific embodiments presented in this specification will hereafter be explained for the condition where $v=c$ and equation (1) is essentially $p=n\lambda$.

In the foregoing embodiments, ruby is used for the laser material 5 and the wavelength λ of the light wave produced thereby is 6943A. A reflection-type diffraction grating made of metal is used for the periodic structure 8 of highly reflective material. It is desirable that the number of grooves by which the period is expressed is 1440 per millimeter when n=1. For the purpose of deriving only a unidirectional component of the light wave, the axis of the ruby bar (i.e., the axis perpendicular to the end faces 5*a* and 5*b*) should be cut to an angle of 60° or 90° with respect to the crystal axis (C-axis) of the ruby. The light wave emitted therefrom is almost perfectly polarized. For obtaining polarization, a polarization plate may be used. The ruby bar provided in said manner is revolved around the axis, and the relation between the polarized face and the periodic structure 8 is adjusted so that the direction of the electric field vector of the light wave becomes perpendicular to the direction of the plural grooves provided on the surface of the periodic structure 8.

By thus arranging the elements, a laser oscillation having the field formed with the periodic strength of the electric field vector of the light wave can be obtained. It was experimentally found that the electrons can be accelerated by means of said laser oscillation. For example, assume that the oscillation output energy of the optical resonator is 4×10^4 watts, the amplitude of the electric field vector at the surface of the periodic structure is approximately 10^7V./m., and the path length at which the light wave exerts its effect on the electrons is 5 mm. Thus the accelerating energy obtainable at best is about 5×10^4 ev.

The invention will be more specifically explained by referring to further embodiments whose accelerating capability is improved.

In FIG. 3, a highly reflective film 6*a* is mounted on a base plate 7*a*. Other reference numerals used in this figure identify elements which correspond to those elements similarly indicated in FIG. 1.

In this embodiment the laser material 5 is inclined to the periodic structure 8; as a result, the light waves 4 derived from the end face 5*b* are directed to the periodic structure 8 not in a direction perpendicular to the periodic structure 8 but at an angle thereto, i.e., at the braze angle θ at which the injected light is concentrated in a certain direction and reflected therefrom. This is done as reflection at a mirror. In order to return the reflected light wave in the direction from which it came, the highly reflective film 6*a* supported on the base plate 7*a* whose effects are the same as those of the light reflective film 6 and the base plate 7, respectively, are disposed as shown in FIG. 3. Thus, the light waves can be sealed into the optical resonator without loss. In this case, the optical resonator consists of three faces: a light reflective film 6, periodic structure 8 and light reflective film 6*a*. It can be said that these three faces serve to effect a positive feedback of the light wave to the laser material 5. It is to be noted that the light wave can be utilized to the extent of about 50 percent in case only the zero-order reflected wave is used. Whereas, according to the previously described embodiment, almost all of the light wave can be utilized.

FIGS. 4*a* and 4*b* are structural diagrams showing another embodiment of this invention: FIG. 4*a* shows a plane view, and 4*b* shows a front view thereof. This embodiment has its principle feature in the provision of a cylindrical lens 16, which is inserted into the resonator and functions to concentrate almost all of the light waves 4 upon the path 3, the light waves 4 of which have been emitted from the end face 5*b* of the laser material 5. At the same time, the lens 16 rearranges the light waves 4 to be parallel light waves which have once been passed through said lens. Then the lens 16 promotes a positive feedback to the laser material 5. As illustrated in the figure, the light wave energy can be utilized at a higher efficiency as the path of the electron becomes thin like a needle. The reference numerals used in the figure, excepting the lens 16, identify elements which correspond to those elements similarly indicated in FIG. 1.

FIG. 5*a* is a structural diagram showing the essential part of still another embodiment of this invention. FIG. 5*b* is a sectional view taken along line V_b—V_b of FIG. 5*a*. The reference numerals used in these figures identify elements which correspond to those similarly indicated in FIG. 1. In this embodiment no lens is used for concentrating the energy of the light wave 4 upon the electron path 3, but this optical resonator is comprised by an annular film 6 having high reflection and supported by a base member 7, an annular laser material 5 and an annular periodic structure 8 supported by a base member 9, each of the elements being concentrically arranged. The charged particles 1 emitted from an electron source 2 pass very near to the surface of the periodic structure 8. In this case, when the diameters of the periodic structure 8 and of the basic body 9 are determined to be sufficiently small with respect to the mean diameter of the laser material 5, the concentration of the light wave energy is increased and thus the light wave can be utilized at a higher efficiency, and the electron-accelerating effect can be remarkably improved. Needless to say, the electron beam may be formed either as a ring or a line.

FIG. 6 is a schematic diagram showing the essential part of still another embodiment of this invention. This embodiment has its important feature in the provision of a rotary prism 17 in place of the highly reflective film 6 used in the embodiment of FIG. 1. The aim of this arrangement is to let the laser material 5 perform giant pulse oscillation. Such giant pulse oscillation can be achieved through the known saturable coloring matter method, or through a combination of these methods. Because these methods are of the known art, the explanation thereof is omitted from this specification.

Now according to this embodiment for which the giant pulse oscillation is adopted, the energy of the light wave 4 in the optical resonator can be made as great as 10^8 to 10^{10} watts at the instant of oscillation. Thus an electron accelerator capable of supplying more than 10^7ev. of energy to the electrons for a path length of 1 cm. can be obtained.

Also in this embodiment, the prism 17 and the periodic structure 8 make up an optical resonator. The periodic structure 8 exerts a positive feedback effect of light wave on the laser material 5.

In the foregoing embodiments, as has been explained, the periodic structure 8 is formed into that which has faces of rectangular periodic structure. However, the structure of sine wave form, as shown in FIG. 7, or of triangular wave form, as in FIG. 8, may be used therein instead of said rectangular periodic structure. In short, the periodic structure necessary for the objects of this invention should at least be capable of exerting a periodic change upon the electric field vector of light wave.

The charged particle accelerator of this invention has been explained by way of example. It is to be noted that there is a phenomenon accompanied by the charged particles travelling along the periodic axis and near the surface of the periodic structure, to induce such light wave energy as will serve to reduce the energy of said charged particles. This phenomenon is identical to the known Smith-Percel effect or the known slow wave amplifying effect in the travelling-wave tube. According to this invention, the light wave produced by the laser oscillation is absolutely predominant over the light wave oscillated due to said accompanying phenomenon. If, however, the amount of current of the charged particles being accelerated is increased to an extreme, the resultant effect will not be negligible, and the subsidiarily produced light wave will become predominant over the primary. Practically, the accelerator of this invention is not intended to cover such extraordinary instance.

Needless to say, neodium doped glass, carbon dioxide gas, steam, or the like may be used on the same principle where ruby is used as the laser material. Further, the accelerating direction of the charged particle is not necessarily to be along the extension from the direction of charged particle emission. For example, the direction of charged particle movement may be changed by applying a magnetic field perpendicular to the path of the charged particle, in the same manner as in the ordinary accelerator.

It is known in the laser art that half-transparent plate is inserted in the optical resonator so as to operate said resonator as a complex-type on the whole, or a light wave mode selection plate is inserted therein. These considerations may be applied to the accelerator of this invention.

The foregoing embodiments are intended to illustrate the examples where an optical resonator is disposed along the path of the electron beam. The invention is not limited to this arrangement, but may be embodied in many ways, for example as in FIG. 9, a plurality of optical resonators (e.g. two resonators) may be disposed along the path of the electron beam if so required. Also, the periodic structure may take various forms such as the sinusoidal structure shown in FIG. 7 and the triangular structure shown in FIG. 8. The reference numerals used in FIGS. 7, 8 and 9 identify elements which correspond to those similarly identified in FIG. 1.

As has been described in detail, the present invention makes it possible to provide a markedly efficient and compact charged particle accelerator, in which the light wave energy can be effectively supplied to the charged particles, thus assuring excellent accelerating performance.

While several embodiments of the invention have been illustrated and described in particular, it is to be understood that the invention is not limited thereto or thereby.

We claim:

1. A device for transferring energy from light waves to charged particles, comprising

with a periodic surface which has a high reflectivity for at least a given wavelength,

first means for directing charged particles to an area located within a distance of 10 times said given wavelength from said periodic surface and said

second means for generating and directing coherent light at said given wavelength toward said periodic surface and through said area to which said charged particles are directed, whereby a variation in the electric field vector of a periodic light wave is produced in the vicinity of said periodic surface thereby accelerating the charged particles.

2. A device as defined in claim 1 wherein said second means is provided in the form of laser device forming with said periodic surface an optical resonator.

3. A device as defined in claim 1 further including third means positioned between said second means and said periodic surface for concentrating the light generated by said second means within the area to which said charged particles are directed.

4. A device as defined in claim 1 wherein said structure is of a cylindrical form and said second means is cylindrical in form and positioned concentrically about said structure.

5. A device as defined in claim 2 wherein the optical axis of said laser device is directed at an angle to said periodic surface, and further including a reflection mirror positioned with respect to said periodic surface transverse to path of reflected light generated by said second means and reflected by said periodic surface.

6. A device as defined in claim 2 wherein said second means is provided in the form of at least two laser devices forming with said periodic surface a pair of optical resonators.

7. A device as defined in claim 1 wherein said structure is provided in the form of a metal plate having a plurality of parallel grooves in the surface thereof facing said second means.

8. A device as defined in claim 7 wherein said charged particles are directed along a path intercepting the path of said coherent light, the parallel grooves in said structure being disposed transverse to the path of said charged particles.

9. A device as defined in claim 8 wherein the pitch of the grooves in said structure is proportional to the wavelength of said coherent light.

10. A device as defined in claim 7 wherein said grooves in said metal plate form a series of parallel rectangular projections on the face thereof.

11. A device as defined in claim 7 wherein said grooves in said metal plate form a series of parallel triangular projections on the face thereof.

12. A device as defined in claim 7 wherein said grooves in said metal plate form a series of parallel sinusoidal projections on the face thereof.

13. A device as defined in claim 2 wherein said laser device includes a reflection mirror and laser material disposed between said reflection mirror and said periodic surface to form an optical resonator, said reflection mirror being provided in the form of a rotary prism.

14. A device as defined in claim 1 wherein said structure is provided in the form of a metal cylinder having a plurality of parallel axial grooves in one surface thereof, said second means being concentric with said metal cylinder and positioned opposite said one surface thereof.

15. A device as defined in claim 14 wherein said grooves are disposed in the outer surface of said metal cylinder and said second means is provided in the form of a laser device including a tubular member of laser material concentric with and disposed about said metal cylinder and a tubular mirror concentric with and disposed about said laser material to form an optical resonator.

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