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PLASMA FORMATION AND PARTICLE ACCELERATION BY PULSED LASER

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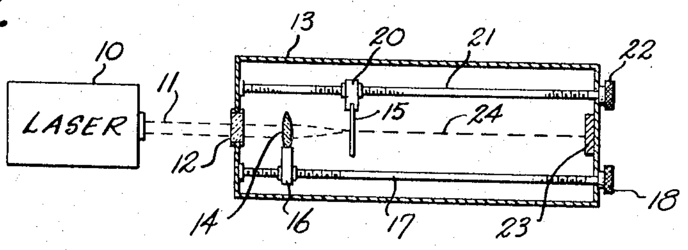
Fig. 1.



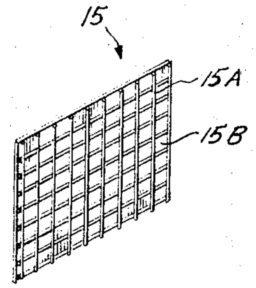


Fig. 1A.

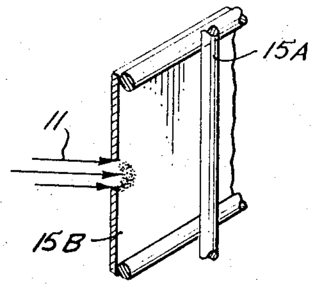


Fig. 1B.

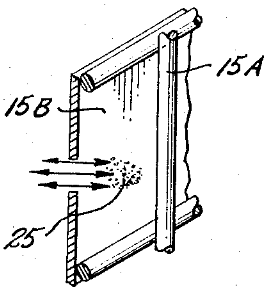


Fig. 1C.

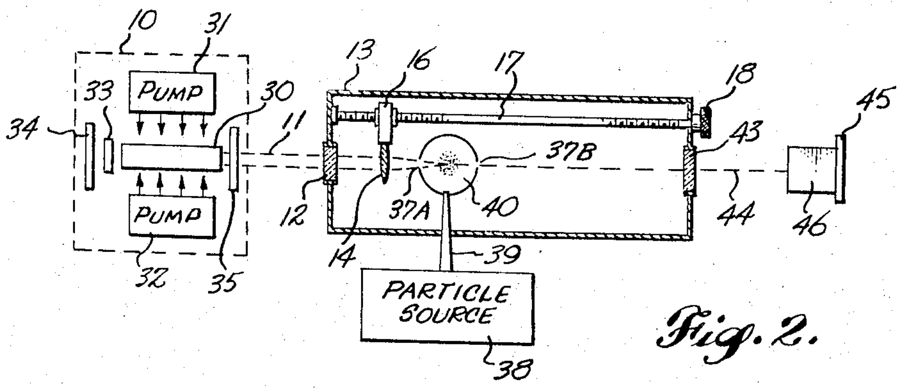


Fig. 2.

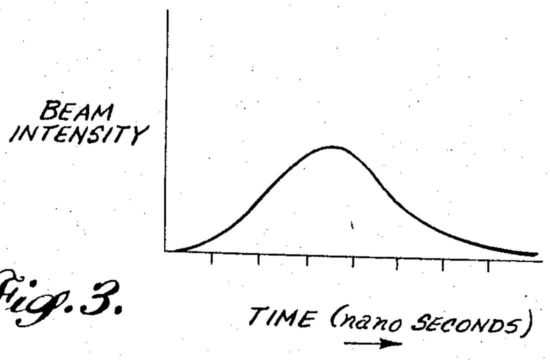


Fig. 3.

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PLASMA FORMATION AND PARTICLE ACCELERATION BY PULSED LASER

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The present invention relates to particle accelerators and more particularly to an improved method and means for accelerating particles to high energies by making use of compact and simplified apparatus.

The many and varied uses for devices capable of accelerating particles such as electrons to a high energy state are well known at the present time. Various techniques and devices have been used for obtaining extremely high energy charged particles with several such devices being capable of producing particles having energies higher than 10^9 electron volts (referred to as bev.). One device for accelerating charged particles is the Van de Graaff generator which employs a conveyor belt and spray points for applying charged particles to the belt. The belt then serves to convey the charged particles to an insulated electrode, generally in the shape of a sphere, where the charges are accumulated until a very high potential exists. Various other types of devices have been developed for accelerating particles, including: the cyclotron which accelerates charged particles to high energies by means of an alternating electric field between two electrodes in a constant magnetic field; the cosmotron (or proton-synchrotron) which is in effect a synchrotron modified to provide acceleration of protrons by means of frequency modulation of a radio frequency accelerating voltage and in which the particles move in a circular orbit in an increasing magnetic field with the alternating electric field being in synchronism with the orbital motion of the particles; and the well-known linear particle accelerators.

While the above and other types of accelerators will provide high energy particles, it is noted that such accelerators have the common characteristic of being relatively large, heavy, and require either an extensive strait path for permitting the particles to travel substantial distances or a heavy magnet assembly is needed to confine the particles to circular orbits. The requirement for such long paths or heavy magnet assemblies together with the need for various other pieces of complex equipment has given rise to costly installations for obtaining particles in the bev. and higher energy range. Also such devices are not readily movable but in general require a permanent installation. In many applications mobility of a high energy particle accelerator is a desirable feature, as for example in the case of mobile X-ray units and accelerators used for laboratory research. Various other advantages and uses for a compact and low cost high energy accelerator will be immediately obvious to those skilled in the art.

It is therefore an object of the present invention to provide an improved method for accelerating particles.

It is another object of the present invention to provide a high energy particle accelerator which is compact in size by comparison to prior art particle accelerators producing particles having energies comparable to those provided by the present apparatus.

A further object of the present invention is to provide a novel method and means for accelerating charged particles such as electrons to extremely high energies by making use of relatively low cost and compact apparatus.

An additional object of the present invention is to provide an improved method for accelerating particles to energies greater than one billion electron volts by making use of relatively compact and lightweight devices.

Another object of the present invention is to provide a novel particle accelerator capable of accelerating charged particles to extremely high energies and wherein the apparatus is lightweight and low in cost by comparison to prior art devices which heretofore have been required for producing high energy particles.

In accordance with the teachings of the present invention the beam from a laser (an optical maser) is focused on a cloud of charged particles which preferably is in the form of a plasma (either metallic or gaseous) or for example which is formed by an accumulation of electrons. The laser can be one of the type well known in the art, as for example the well-known ruby laser, and is preferably of the type which is capable of providing energy of greater than a few tens of gigawatts. Ruby lasers having this energy capability are well known and available at the present time, but in accordance with the concepts of the present invention the energy output of the selected laser is chosen according to the desired particle energy. The cloud of charged particles in the form of a plasma or an accumulation of electrons is established with a density such that electromagnetic radiation in the visible or near-infrared region will be reflected. One method to be utilized in accordance with the invention for obtaining the cloud of particles is to focus the beam of a high energy laser on a small area of a thin metallic film or sheet of metal foil in a manner such that the laser beam serves to first rapidly vaporize the metal and thereby generate a high density plasma. The laser beam is then focused on the resulting high density plasma and according to the laws of conservation of energy an interchange of momentum occurs between the charged particles and the laser beam photons. The result is that the energy carried by the photons in the laser beam is transferred to the charged particles giving rise to high energy particles. The largest momentum transfer between the laser beam and the charged particles takes place when the beam is totally reflected from the charged particles. It should be noted, however, that the difference in momentum transfer between reflection and absorption is only a factor of two.

In order to reflect most of the laser beam radiation the frequency of the plasma of charged particles is selected to be higher than the frequency of the laser beam energy. Using a ruby laser and a high density metallic plasma, energies of 10^9 electron volts and higher can be obtained when the laser has an output power capability in the order of several gigawatts.

In another embodiment of the invention a cloud of electrons having a high density is formed by a special electron accelerator commonly referred to as a plasma electron beam source. The plasma beam source makes use of a cylindrical or spherical cavity in which an ionized plasma is formed with a small aperture being provided for exit of high energy electrons. In view of the electron density required in the cloud the electron source is preferably operated in a pulsed manner at a very high current. The laser beam is directed through an appropriate opening in the wall defining the the cavity and is focused on the high density cloud of electrons therein. The resulting interaction and transfer of momentum between the laser beam and the electrons causes the electrons to achieve energies greater than one bev. depending upon the laser energy per unit area. Thus a low cost source of very high energy particles is provided without the need for the heavy and bulky assemblies associated with prior art high energy accelerators. The resulting high energy particles may be directed to hit a suitable target for the production of very high energy X-rays.

As described in detail hereinafter the application of power to the laser can be so controlled that the radiation pressure will be sufficient to overcome the charge separation in a metallic plasma and hence cause acceleration of the freed electrons. If the laser power is supplied at an appropriate slower rate ions as well as electrons will be accelerated. Thus the method and apparatus makes possible the acceleration of electrons or of a plasma.

The above as well as additional advantages and objects of the present invention will be more clearly understood from the following description when read with reference to the accompanying drawing wherein,

FIGURE 1 is a side view in diagrammatic form (and including a vacuum chamber in cross section) of one embodiment of the present invention for producing a high density cloud of particles from a piece of metal foil and for then accelerating the resulting particles to high energies;

FIGURE 1A is an enlarged isometric view of the metal film and support assembly shown in FIGURE 1;

FIGURE 1B is an enlarged isometric view of approximately one-half of one of the square areas of the thin metal film of FIGURE 1A having the laser beam focused thereon and illustrating the initial formation of the plasma;

FIGURE 1C is an enlarged isometric view of a part of the thin metal film and corresponding in general to FIGURE 1B but showing the cloud of particles as having been formed by the laser beam and being subjected to continued radiation by the beam;

FIGURE 2 is a side view in diagrammatic form (with the vacuum chamber in cross section) of an embodiment of the invention which includes an external source of particles arranged to provide a properly located high density cloud of particles in the path of the laser beam; and

FIGURE 3 is a graph of relative laser beam intensity versus time for illustrating the manner in which the laser beam is used to first generate a plasma and then to accelerate all or part of the resulting particles.

Referring now to the drawing and in particular to FIGURE 1 there is shown for purpose of illustration a conventional laser indicated generally at **10** and adapted to provide an output beam of electromagnetic radiation indicated at **11**. The laser **10** may for example be a ruby laser adapted to operate with a power output in the order of 1 or more gigawatts. The beam **11** passes through window **12** which is transparent to the radiation from the laser **10**. The window **12** will be seen to be embedded in the left end of a vacuum chamber **13** which is evacuated by conventional apparatus. The beam **11** is focused by the lens **14** onto a suitable source of particles indicated as the target **15** which, as described in greater detail hereinafter, is preferably in the form of a thin metallic film appropriately supported. It will be seen that the lens **14** is secured to a lens holder **16** which is in turn carried on a threaded shaft **17** supported by appropriate bearings in the end of the chamber walls **13** and having an adjustment knob **18** disposed outside of the chamber **13**. In a similar manner the laser target **15** is held by the target holder **20** which is similarly supported for longitudinal adjustment on the threaded shaft **21** having an adjustment knob **22** disposed outside of the evacuated chamber **13**. Any desired object **23** which is to be bombarded by the particles is positioned in the path thereof. The stream of high energy particles is indicated by the dashed line **24**.

As explained in greater detail hereinafter, the beam of electromagnetic radiation provided by the laser **10** is focused on a small area of target **15** to thereby produce a high energy concentration for creation of the required plasma. The thickness of the metal film is selected in accordance with the penetration depth of the laser beam being used so that there will be a substantially complete transfer of energy from the laser beam to the volume of metal film on which the beam is focused. By thus selecting the thickness of the metal film an extremely rapid vaporization of the metal takes place to thereby give rise to the required high density plasma. Since the thickness of the film may be in the order of a few thousand Angstrom units it is found that the film itself does not possess sufficient rigidity to permit accurate positioning thereof in the path of the laser. Accordingly, the film is supported by a fine mesh wire screen as illustrated in FIGURE 1A wherein it will be seen that a wire mesh **15A** serves to support a thin film of any selected metal indicated generally at **15B**. This will also be seen more clearly in FIGURE 1B which is an illustration of a greatly enlarged section of the target **15** showing the laser beam **11** as being focused thereon and at an instant of time when the laser beam is in the process of vaporizing a small portion of the metal film **15B**. The isometric view of the small section of the target metal is shown in FIGURE 1C at a time shortly after the laser beam has vaporized the metal and has caused the high density plasma to be generated. In the illustration of FIGURE 1C the cloud of plasma indicated generally at **25** is still of sufficient density to cause substantially total reflection of the laser beam and hence a maximum interchange of energy from the laser beam to the plasma takes place.

When the plasma is formed it is at a very high temperature and undergoes rapid expansion until the density thereof decreases to a value where the cloud is no longer of sufficient density to cause reflection of the laser beam. However, due to the rapid rise time of the laser pulse as compared to the rate of expansion of the cloud of plasma, a sufficient energy exchange takes place for particles to be accelerated to energies greater than 1 bev. As seen in FIGURE 1 the high energy particles indicated generally at **24** are directed toward a suitable object which may be termed a particle target indicated at **23**. The target **23** may for example be a suitable slab of metal for the production of high energy X-rays in response to the bombardment thereof by the high energy particles.

The manner in which the laser beam **11** is able to first generate the high density plasma and to then cause acceleration of the resulting particles will be more clearly understood if the nature of a cloud of charged particles such as a metallic or gaseous plasma is considered. As discussed hereinafter, the high density cloud of charged particles can also be an accumulation of electrons. The magnitude of the force being produced by the focused laser beam **11** will be evident from a consideration of the force exerted on a surface when a light beam is reflected therefrom. The force F is:

$$F=\frac{kE}{c\tau} \tag{1}$$

where

c is the velocity of light,

E/τ is the power of the laser pulse, and

k is between 1 and 2, depending on the Doppler shift and whether the beam is reflected or absorbed.

Using a ruby laser having pulse power in the order of several gigawatts (1×10^9 watts) it will be seen that substantial forces are produced. For example using a ruby laser having a pulse power of 2×10^{10} watts it will be seen that the force is approximately 10^7 dynes. A laser beam can be focused to an area that is limited only by diffraction and is given by πd^2, with

$$d=\frac{1\cdot22\lambda}{D}f \tag{2}$$

where d is the diameter of the first circle of confusion, λ is the wavelength of light, D is the aperture of the laser, and f is the focal length of the lens. For $\lambda=7\cdot10^{-5}$ cm. (typical for a ruby laser), $D=1$ cm., and $f=1$ cm., d is equal to about 10^{-4} cm. Approximately 84% of the energy falls inside this diameter. Hence, the pressure in atmospheres is

$$p=\frac{F}{A}\simeq\frac{10^7\cdot10^{-6}}{10^{-8}}=10^9 \text{ atm.}$$

The acceleration of particles by the reflection of a laser beam from a plasma or electron cloud can be described by the following conservation laws (of momentum and energy):

$$\frac{nh\nu}{c}=-\frac{nh\nu'}{c}+Nm_0v\gamma \tag{3}$$

$$nh\nu=nh\nu'+Nm_Oc^2(\gamma-1) \tag{4}$$

where:

n is the number of photons that interact with the electron cloud,
h is the Planck constant,
ν is the frequency of the incident beam,
ν' is the frequency of the reflected beam,
c is the velocity of light,
N is the number of particles in the absorption volume of the focal point of the beam,
v is the velocity of the recoiling electrons, and

$\gamma=1\sqrt{1-\nu^2/c^2}$

For $v\approx c$ (3) and (4) can be written as

$$\frac{nh\nu}{c}=Nm_0c\left(\gamma-\frac{1}{2}\right) \tag{5}$$

$$\frac{nh\nu'}{c}=Nm_0c\left(\frac{1}{2}\right) \tag{6}$$

The greatest transfer of momentum from the laser beam to the cloud of charged particles takes place when the beam is totally reflected (the difference in momentum transfer between reflection and absorption being a factor of two). In order to reflect most of the radiation, the plasma frequency of the collection of charged particles must be higher than the frequency of the laser beam. For a ruby laser, the frequency of the emitted radiation is $4.35\cdot10^{14}$ sec.$^{-1}$. The plasma frequency is given by

$$\nu_p=8.9\cdot10^3\sqrt{n_e} \tag{7}$$

where n_e is the electron density. Equating these two frequencies gives

$$n_e=2.4\cdot10^{21}\text{ electrons/cm.}^3$$

This electron density can either be produced in a metallic plasma or an electron cloud. Metallic plasmas have a density between 10^{22} and 10^{24} electrons/cm.^{3} For presently available giant pulse lasers, rise times are of the order of 10^{-9} sec. as seen in FIGURE 3. The thermalization time for ions and electrons is given by

$$t=[1.05\cdot10^{13}A/n_eZ\ln\Lambda]T^{3/2} \tag{8}$$

where:

$$\ln\Lambda=\ln\frac{v_T}{\nu_p p_{min}}\cong10$$

and:

T is the temperature in kev.,
A is the atomic weight,
n_e is the electron density,
Z is the ionic charge number,
v_T is the thermal velocity of electrons,
ν_p is the plasma frequency, and
p_{min} is the minimum impact parameter.

For example, for metallic electron densities with $T=1$ kev., $t<10^{-10}$ sec. Since the rise time of power in the giant laser pulse is longer than 10^{-10} sec., the electrons and ions in the plasma are initially in thermal equilibrium. Using the metal foil **15B** as the laser target, its thickness is chosen such that when the laser pulse power reaches a maximum the plasma has an electron density greater than 10^{21} cm.$^{-3}$ and therefore is still reflecting. The lower limit for the thickness of the metal film is set by the penetration depth of a laser beam in a metallic plasma, approximately 3000 A. for $n_e=10^{22}$.

There are about 10^9 free electrons in a cubic micron of metal which is the approximate volume of the metal vaporized by the laser beam in FIGURE 1. To separate these electrons from the same number of ions, the maximum force necessary is:

$$\frac{N^2e^2}{r^2}=\frac{(10^9\cdot4.8\cdot10^{-10})^2}{(10^{-4})^2}=2.24\cdot10^7\text{ dynes}=22\text{ kg.}$$

where N is the total number of electrons to be separated from ions, r is the radius of the plasma cloud, and e is the electron charge. This is to be compared with the radiation pressure available from the laser beam. When the radiation pressure is sufficient to overcome the charge separation, only the electrons are accelerated. If the laser energy is applied more slowly ($<10^{19}$ watts/cm.^{2}) the ions will be dragged along with the electrons. Therefore, depending on the power of the laser beam and the total number of electrons, either an electron accelerator or a plasma accelerator is provided. From the above equations it will be seen that with a laser power of a few tens of gigawatts particles with energies considerably greater than 10^9 ev. are produced.

As set forth above, a cloud of electrons of density $>10^{21}$ cm.$^{-3}$ will reflect a ruby laser beam. To produce a sphere of electrons of radius 10^{-4} cm., with a density $n_e=10^{21}$ cm.$^{-3}$, they must be accelerated to energies of

$$\frac{Ne^2}{r}=\frac{10^9(4.8\cdot10^{-10})^2}{10^{-4}}\cong1.4\cdot10^6\text{ ev.}$$

per electron, and focus them to an area of 10^8 cm.^{2}. To have at any time during the laser pulse the required electron density, the current has to be larger than 10^4 amps. This necessitates a pulsed operation of the electron beam.

Referring now to FIGURE 2 it will be seen that the apparatus for accelerating electrons produced by an independent source makes use of a well known and compact laser apparatus **10** which includes a laser rod **30** which may be a ruby rod. A pair of optical pumps **31** and **32**, such as xeon flash lamps, are positioned to selectively irradiate the laser rod **30**. A selectively actuated shutter assembly or Q-switch **33** is positioned between the left end of the rod **10** and a first reflector **34** having a completely reflective surface. A second reflector **35** adjacent the right end of the rod **10** is only partially reflective and is adapted to permit the passage of the desired laser beam **11** therethrough. As is well known in the art, the pumps **31** and **32** serve to provide sufficient energy to the optical cavity provided by the laser rod **10** to cause atoms in the rod to become excited to a metastable condition. When such atoms return to their stable condition photons are released which travel down the rod and initiate the now well-known laser action. By maintaining the Q-switch **33** in a closed condition until there is a substantial population inversion between the number of atoms in the stable and metastable conditions, the usual series of short duration and relatively low intensity bursts of radiation are suppressed. Then when the Q-switch is opened to permit the reflection of energy by the reflector **34** a major burst of energy is obtained. The relative intensity of a typical high intensity output pulse versus time is illustrated in FIGURE 3.

In the apparatus of FIGURE 2 it will be seen that the lens **14** inside the vacuum chamber **13** serves to focus the beam **11** through a first opening **37A** in the spherical plasma chamber **37**. A suitable particle source **38**, which may be a high energy electron source, is coupled with plasma chamber **37** by the evacuated tunnel **39** and serves to provide a high density electron cloud **40** inside the chamber **37**. The particle source and chamber **37** can be one of a number available at the present time capable of providing the above indicated required electron density in the path of the laser beam **11**. As set forth above, the laser beam interacts with the electrons with a transfer of momentum taking place and a stream of very high energy electrons **41** emerging through opening **37B**. A suitable metal target **43** secured in the end wall of the vacuum chamber is bombarded by the high energy electrons causing high energy X-rays **44** to be generated. For purpose of illustration the X-rays are shown as being directed to a suitable photographic plate **45** after passing through an object **46** which is to be X-rayed. As is well known in the art the resulting X-rays are of very short wavelength and thus of high energy since the electrons giving rise to the X-rays are of very high energy.

Since the above described apparatus, including the presently available high energy lasers, is compact and low in cost by comparison to previous particle accelerators capable of producing particles having the energies above indicated, it will be seen that an improved method and means for accelerating particles to high energies has been provided. The in-principle upper limit of acceleration of many devices is established by the bremsstrahlung losses, which in the case of linear acceleration becomes significant only when the particle gains energy equivalent to the rest energy within the classical electron radius. Thus for all practical purposes the bremsstrahlung limitation on acceleration of particles is removed in the case of linear acceleration of particles. Accordingly the present invention makes use of a laser to provide acceleration of particles to energies heretofore unattainable.

While the invention has been described by reference to specific apparatus and methods for purpose of illustration, it is to be understood that those modifications obvious to a person skilled in the art from the teachings hereof are considered to be encompassed by the following claim.

What is claimed is:

The method of accelerating particles comprising the steps of focusing the output beam of a pulsed laser on a thin metal film having an initial thickness substantially equal to the penetration depth of the laser radiation, the energy of said pulse being sufficient to vaporize the irradiated portion of said film during its rise time, thereby forming a plasma sufficiently dense to reflect said radiation, and maintaining the laser beam focused on said plasma during the persistence of said reflective density to cause an interchange of momentum immediately following formation of said plasma.

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