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A PHASE ADJUSTED FOCUSING LASER ACCELERATOR

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Abstract

In this paper a proposal is discussed to accelerate charged particles by an axially symmetrical electromagnetic field of a focusing laser. The axis of the field is the equilibrium orbit of the charged particles. It is shown that the charged particles can be focused transversally and longitudinally in the field. For continual acceleration of the charged particles, the phase of the incident laser has to be suitably adjusted. It is estimated that with an incident power density of 5×10^{10} W/cm^2, the effective energy gain for such an accelerator may be as high as 90 GeV/m, so the size and the cost of a Phase Adjusted Focusing Laser Accelerator (PAFLA) may be drastically reduced. This seems to offer an economical way to a super high energy accelerator.

Introduction

The progress of high energy physics has always been associated with the development of accelerators of higher and higher energy. The size and cost of a machine accelerating particles to such high energy as 10 Tev, for example, would be formidable if it were built in the usual way. In order to reduce this, it is most important to increase the energy gain per unit length of the accelerator. High frequency power sources are used in the usual accelerators and the accelerating field obtained is limited by the power density. Stronger electromagnetic fields are available with a high power pulsed laser and even stronger fields can be made available by focusing. For example, in connection with the pulsed laser fusion program, the power density at the focus is as high as 10^{17} - 10^{18} W/cm which corresponds to an electric field of 10^{10} V/cm. As the focus is far away from the material and lies in vacuum, the power density there can be made to exceed by orders of magnitude the limit which materials can tolerate. Hence, if particles can be accelerated with the electric field of a pulsed focusing laser, the size, and with it the cost, of a super high energy accelerator will be drastically reduced.

Many proposals for laser accelerators have appeared in recent years,[1-11] mostly working on a slow wave pattern of the field. The accelerating field strength is limited by the breakdown strength of the material or the medium. It seems so far as super high energy is concerned, that laser accelerators working with a slow wave field pattern will compete somewhat unfavorably.

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In the present paper it is proposed to accelerate the charged particles along the axis of an axially symmetrical electromagnetic field of a focusing laser. The phase velocity along the axis of the focusing field is, quite the contrary to what is usually the case, larger than that of light in vacuum. It is easily shown, by studying the dynamics of the charged particles, that conditions for the focusing of the orbits transversally and longitudinally agree with one another under very wide conditions without additional lenses. In this way, it is possible to obtain an accelerating field, higher by many orders of magnitude than that limited by materials. But the phase velocity of the accelerating field is also larger than the velocity or the particles, so it is necessary to adjust the initial phase of the initial phase of the incident laser by a certain amount after a certain short distance along the axis. It appears at first sight that the sooner the phase adjustment the better the acceleration, but we must remember that the phase adjustment is done on the wall of the accelerating tube and what we needed is the change of phase for the field on the axis. Boundary value problem calculations based on Maxwell's equations show that, for an accelerating tube of a radius of ten thousand wavelengths, the distance for phase adjustment cannot be chosen smaller than a wavelength or the change of phase will be completely blurred on the axis. Taking this into account, it is estimated that with an incident power density of the laser of 5×10^{10} W/cm, which can be tolerated by the material of the wall of the accelerating tube, the effective energy gain may be as high as 90 GeV/m. Thus, PAFLA seems to offer a new way to super high energy accelerators with drastically reduced size and cost. Such an accelerator can be used for protons, electrons and, more favorably, for short-lived particles.

Acceleration by a Focusing Laser Field

Take, for simplicity, a laser accelerating tube of an inner radius larger than the laser wavelength by many orders of magnitude. Consider the axially symmetrical TM wave and use cylindrical coordinates z, r and θ. The non-vanishing components E_z, E_r and B_θ, as functions of z, r and the time t, are of the general form

$$E_z = \mathrm{Re}\sum_h E_h J_o(k_{\perp h} r) \exp\,(ihz - i\omega t - i\alpha_h)$$

$$E_r = \mathrm{Re}\sum_h E_h(- ih/k_{\perp h}) J1(k_{\perp h} r) \exp\,(ihz - i\omega t - i\alpha_h)$$

$$cB_\theta = \text{Re}\ E_h(-ik/k_{\perp h})J_1(k_{\perp h}r)\exp(ihz - i\omega t - i\alpha_h) \quad (1)$$

with

$$h^2 + k_\perp^2 = k^2 = \omega^2/c^2 = (2\pi/\lambda)^2$$

and

$$\varepsilon = \mu = 1$$

Here c is the velocity of light in vacuum and with the Bessel functions $J_0(x)$ and $J_1(x)$ satisfying

$$J_0' = -J_1,\ (xJ_1)' = xJ_0$$

Maxwell's equations have been satisfied. The laser wavelength in vacuum is denoted by λ and the longitudinal and transversal components of the laser wave vector, by h and $k_{\perp h}$, the suffix h referring to the partial wave. Thus, E_h and α_h denote the magnitude and phase of the z-component of the electric field on the axis of the partial waves. In the summation only those partial waves with $h < k$ contribute to the focusing field on the axis, the other partial waves with $h > k$, being evanescent surface waves, decay exponentially away from the wall of the accelerating tube. From the properties of the Bessel function $J_0(x)$, namely

$$J_0(0) = 1 \text{ and } J_0(x) = (2\pi x)^{-\frac{1}{2}}\{\exp i(x - \pi/4) + \exp -i(x - \pi/4)\}$$

as $x >> 1$, introduce a focusing factor F as an estimate of the ratio between the peak value of the z-component of the electric field on the axis and that of the incident wave on the wall, namely

$$F = E_z(0)/E_z(r)_{inc} = (2\pi k_\perp R)^{\frac{1}{2}} \quad .$$

Where R is the radius of the accelerating tube and $E_z(r)_{inc}$ is the incident field on the wall.

Intuitively, the above focusing field can be realized by an axially symmetrical converging wave with its electric field polarized in the plane of incidence. A cross-section of the focusing field is shown in Fig. 1. Thus, it is found $k_\perp = k\sin\theta$, $h = k\cos\theta$ and $h < k$ is satisfied. The focusing factor can be written as

$$F = 2\pi(R\sin\theta/\lambda)^{\frac{1}{2}} \quad . \quad (2)$$

Denoting the peak value of the incident electric field at the wall by E_W so that the incident power density is

$$P = cE_W{}^2/8\pi \quad (3)$$

(ε,μ of the incident region also taken as unity) and noting from Fig. 1 that $E_z(R) = E_W\sin\theta$, it is found, approximately, that:

$$E_h = E_W\ F\sin\theta = E_W 2\pi(R/\lambda)^{\frac{1}{2}}(\sin\theta)^{3/2} \quad (4)$$

Now consider the motion of the charged particles in the field of the focusing laser. Although their energy gain may be very large (say 100 GeV/m), the energy gain per laser wavelength λ is very small (say, 0.1 MeV per $\lambda = 1\mu$) compared to the rest energy of the charged particle. Neglecting many body effects, one may treat the motion of the charged particles by perturbation methods and in the first approximation consider each partial wave separately. The partial wave which is referred to above as the principal propagating mode, contributes most to the acceleration and it alone will be discussed below.

For the particles moving along the equilibrium orbit, $r = 0$, i.e., the z-axis, to the zeroth approximation the equation of path: $t = t_o - z/(c\ \beta)$, corresponding to the free motion. So, the force acting on the particles is, to the first approximation, given by:

$$eE_z = eE_h\ \text{Cos}\Delta$$

where

$$\Delta = \{a_h + t_o + (K^{-1} - h)Z\} \quad (5)$$

is the phase of the accelerating field as seen from the moving particle. The condition for acceleration is simply

$$e\cos\Delta > 0 \quad \cdot \quad (6)$$

Since t_o denotes the instant when the particle passes $z = 0$ with velocity $c\beta$, the condition for longitudinal focusing demands a greater acceleration for the late-coming particles, or a smaller acceleration for the faster particles. That is, either $\partial(e\cos\Delta)/\partial t_o < 0$ or $\partial(e\cos\Delta)/\partial\beta < 0$, gives the condition

$$e\sin\Delta < 0 \quad \cdot \quad (7)$$

For particles moving in the neighborhood of the equilibrium orbit, the transverse force is, to the first approximation, given by

$$f_\perp = -(r/2)(h - k\beta)cE_h\sin\Delta \quad \cdot$$

Since for the propagating mode of the focusing accelerating field we have $h < k$, it is possible to choose h and β to satisfy the rather wide condition

$$(h - k\beta) < 0 \quad , \quad (8)$$

in which case the condition for the transverse focusing coincides with that for the longitudinal focusing, namely Eq. 7. No additional magnetic lenses are needed. This is so, as may be seen from the two terms on the left hand side of Eq. 8, because the transversal force due to the magnetic field overcomes that due to the electric field.

From Eqs. 5 to 8 it may be seen that it is possible to accelerate charged particles with simultaneous focusing by properly adjusting the phase of the accelerating field as seen from the moving particles. For protons, it is limited to within the fourth quadrant, for electrons to within the second quadrant. Owing to the dependence of Δ on z, to continually accelerating the charged particles along the axis, it is necessary to change the phase α_h of the incident laser for the above conditions to be continually satisfied.

Phase Adjustments

From Eq. 5 it follows that the phase of the accelerating field, as seen from the moving particles, will change by $\pi/2$ after the particles have travelled a distance ℓ along the axis, where

$$\ell = (\lambda/4)\ (\beta^{-1} - \cos\theta)^{-1} \quad . \tag{9}$$

This will be referred to as the distance for phase adjustment. To compensate for the increase of Δ by $\pi/2$ we may change the phase α_h of the incident wave by lengthening the optical path by a quarter wavelength for every distance. For phase adjustment, as shown in Fig. 2, the wall of the accelerating tube works then as a cylindrical grating, with grating constant $D = 4\ell$, ruled in four steps. According to Eq. 9, for small θ, the distance for phase adjustment can be made very much larger than the wavelength of the laser, so the change of phase along the axis is guaranteed by elementary optics, but the accelerating field is then reduced in accordance with the factor $(\sin\theta)^{3/2}$ of Eq. 4. For a higher accleration we prefer to choose a bigger $\sin\theta$ and hence a shorter ℓ/λ. It becomes then vitally important to see that diffraction effects do not cause the change of phase on the axis to become completely blurred.

Some numerical calculations were made with Maxwell's equations, solving the appropriate boundary value problem.[12-13] Primary calculations for the case of normal incidence show, taking $R/\lambda = 10^4$ for example, that the change of phase on the axis varies linearly with the change of optical path on the wall, as shown in Fig. 3, provided that $\ell/\lambda \geq 1$ is satisfied. The fraction η of the region on the axis where the change of phase is blurred increases rapidly as ℓ/λ becomes smaller than unity, as indicated in Fig. 4.

The distance for phase adjustment depends also on the velocity of the charged particles. For particles of high energy, the variation in β is slight. For simplicity, choose the grating constant fixed but introduce some leap steps as leap days are introduced in the calendar, the distance from one leap step to the next may change in a long accelerating tube. In view of the fact that allowance, however strict, will accumulate in the long run, it is suggested that the accelerating tube be made by fitting together a large number of sections after testing and additional proper measures taken during fitting.

A Conceptual Design

Among the many possibilities of building up an axially symmetrical focusing laser field, one will be described here in more detail. In Fig. 5a, the ring-shaped laser output from a confocal resonator, after going through a special polarizer, is largely reflected at the 45 degree cone-shaped beam splitter and is made incident almost perpendicularly onto the accelerating tube. The outer surface of the tube is ruled for phase adjustment, as discussed above, and the inner surface is ruled as a diffraction grating, such that a large proportion (say η_θ) of the incident energy will go into the diffracted beam of a definite direction with the longitudinal component of the wave vector as required (i.e., with $h = k\sin\theta$, see Fig. 5b). In order to make the best use of the laser power, as indicated in the block diagram Fig. 6, the successive laser amplifiers are properly delayed in time so that the radiation of the laser and passage of charged particles along the axis may synchronize. The coherent length of the laser should be longer than the distance between the successive amplifiers.

Energy Gain

From the above discussion one can estimate the energy gain K per unit length of the accelerating tube from the component of the electric field on the axis, as given by Eq. 4, by multiplying it with the utilization factors for the blurring $(1 - \eta)$ and for phase averaging

$$\eta_\Delta = \quad \cos\Delta\ d\Delta/(\Delta_2 - \Delta_1) \quad , \tag{10}$$

the phase Δ varying uniformly from Δ_1 to Δ_2. Then for the energy gain per unit length of the accelerating tube, it is found that:

$$K = eE_W 2\pi(\eta_\theta\ R/\lambda)^{\frac{1}{2}}\ (\sin\theta)^{3/2}\eta_\Delta\ (1 - \eta) \quad , \tag{11}$$

where η_θ denotes the utilization factor for energy diffraction. Let τ denote the pulse width of the laser and take 20 joules per square centimeter for the pulsed energy tolerated by the material of the wall. Then:

$$\tau p = cE_W{}^2/8\pi < 2.10^8 \text{erg/cm}^2 = 20 \text{ joules/cm}^2 . \tag{12}$$

Evidently K varies as the square root of P. For high acceleration, short pulse is preferred, but the pulse must be long enough to guarantee the required coherent length.

$R/\lambda \sim 10^4 \qquad \ell/\lambda \sim 1 \qquad \sin\theta = .66(\cos\theta = .75)$

$\tau = 3 \times 10^2 \text{sec} \qquad P = 5 \times 10^{10}\ \text{W/cm}^2$

$E_W + 6 \times 10^6\ \text{v/cm} \qquad \eta_\theta = .9$

$\eta_\Delta \sim .75 \qquad (1 - \eta) \sim .65$

and get $K \sim 90$ GeV/m. To accelerate charged particles to an energy of W = 1 Tev with laser wavelength $\lambda = 1\mu$ requires at least the total laser energy Q ∿ 105 x 10^3 joules and the total length of the accelerating tube L ∿ 11 meters with R = 1 cm radius.

To conclude, it is seen that for the realization of the PAFLA a number of new problems will be involved which, however, it seems, are just suitable to be solved by optical means. If the process of photo replica can be adopted in the manufacture of the accelerating tube, then PAFLA for 10 Tev energy becomes conceivable.

The authors are grateful to have benefited from discussions on various occasions with a large number of persons working here on the usual accelerators and elsewhere on lasers and it is a pleasure to thank them all collectively. Specifically we express our thanks to Professor Chu Chi-ho for his suggesting the special polarizer, and to Mr. Wu Jianwu for his writing the early version of the computer program.

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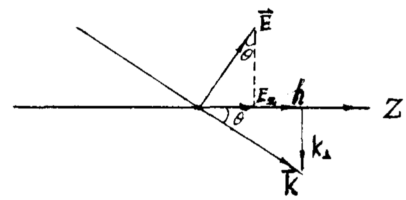

Fig. 1 - Pattern of the accelerating field E_z of the focusing laser, the wave vector k revolving around the Z-axis.

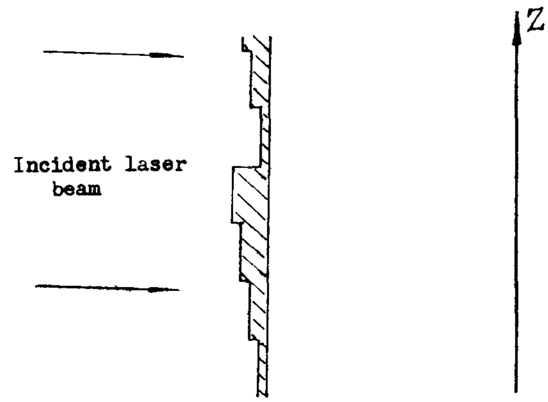

Fig. 2 - Stepwise grating (schematic) for phase adjustment, the grating and the incident laser revolving together around the Z-axis. For a four-step grating the optical path is increased by a quarter wavelength for each step.

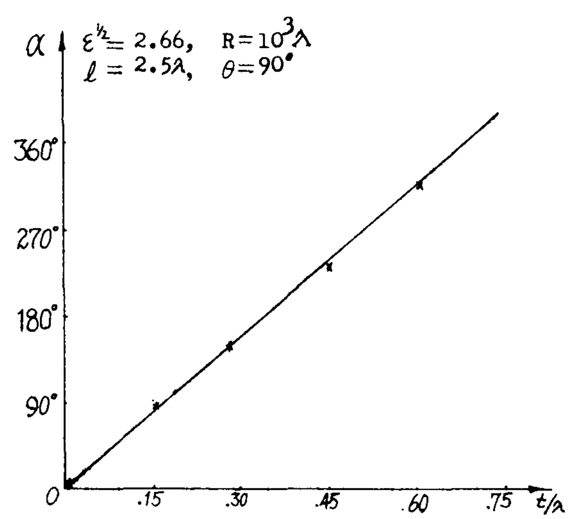

Fig. 3 - Variation of the phase delay α of E_z on the axis for various of the thickness t of step.

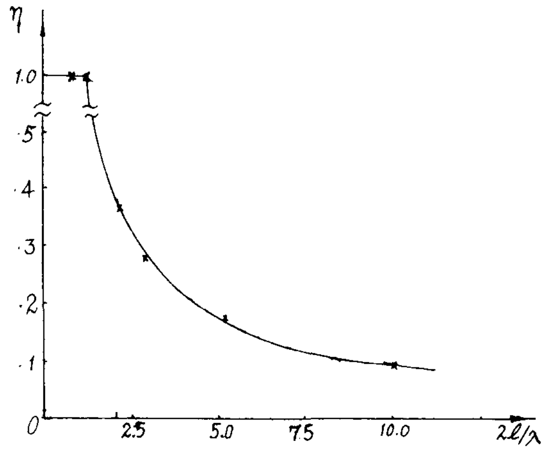

Fig. 4 - Variation of the fraction η of the region on the axis where the change of phase is blurred for various values of grating constant D = 2.

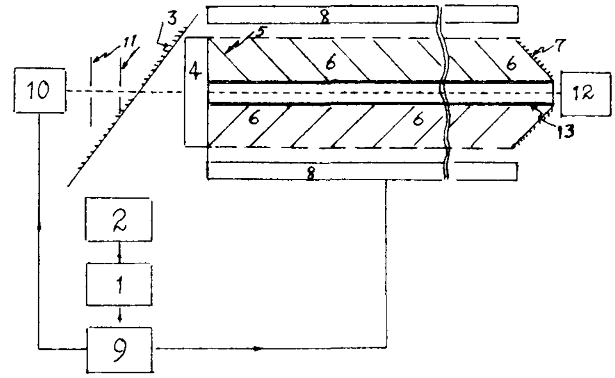

Fig. 6 - A PAFLA block diagram
1. Laser oscillator, 2. Laser amplifier, 3. Reflector, 4. Special polarizer, 5. 45° cone-shaped beam splitter, 6. Laser amplifier, 7. 45° cone-shaped reflector, 8. Pumping source, 9. Time-delayed trigger, 10. Injector of charged particles, 11. Collimating slit, 12. Detectors of charged particles, 13. Accelerating tube.

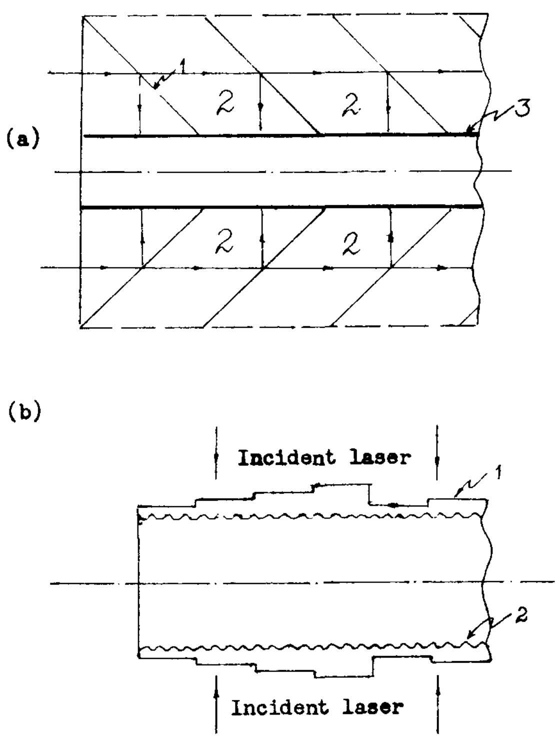

Fig. 5 - The accelerating tube
(a) Arrangement: 1. Beam splitter, 2. Laser amplifier, 3. Accelerating tube.
(b) Structure: 1. Grating for phase adjustment, 2. Grating for diffraction.

Discussion

Teng, Fermilab: I did not quite follow the details of your scheme. But generally speaking there are two difficulties with laser accelerators: (1) because of the very small wavelength, the acceptance of the field is too small; (2) the fabrication precision and operating stability required are very high. Can you comment on these in relation to your scheme?

Zhuang: Yes, we have not gotten into the required accuracy and detail, but it is expected to be very high. However, it seems to us, the problem can be suitably solved by optical means.

Blewett, BNL: Do you plan experimental tests of these ideas?

Zhuang: We want to explore the theoretical before we start on the experimental program.