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LASER-DRIVEN ELECTRON ACCELERATORS

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I. Introduction

An alternative title for this paper could be: "How to build a greater than 1 TeV electron accelerator," since this question provides the motivation. A circular 1 TeV machine is quite impractical from synchrotron radiation considerations. The accelerator has to be linear. If built conventionally like SLAC with 10 MeV/m it would be longer than 100 km which seems unreasonable. Clearly, higher field gradients are needed. There seems reason to hope for fields up to 100 MeV/m from extensions of existing technology but that seems about as much as can be expected. Even with this field the accelerator will be 10 km long. Still higher fields are needed, and for higher fields we naturally turn to the use of lasers.

Lasers exist with powers of about 10^{14} watts, and at the focus of beams from such lasers fields exist of the order of 2 TeV/m. Unfortunately, however, a relativistic particle passing through such a focus receives no acceleration at all. Why is this so?

I will assume (1) Maxwell's equations are correct, (2) the particle to be acclerated is sufficiently relativistic that its motion is approximately along a straight line and its velocity is constant ($\sim$c); (3) the interaction with the light takes place in a vacuum; and (4) the interaction takes place far ($\gg \lambda$) from all dielectrics or conductors. From 3 and 4 it follows that all fields seen by the particles are "far waves" and can be represented as a sum of transversely polarized plane waves with different directions all traveling at the velocity of light. Then from 2 we can deduce that the forces on the particles in the beam can be represented as a sum of oscillating forces from each of the component plane waves. The acceleration of the particle will be the linear sum of the contributions from each wave. The forces from any one wave are, however, oscillatory and the contribution from any such wave is zero. It follows therefore that the acceleration from any arrangement of such waves is also zero. In order to achieve acceleration we must depart from one of the four assumptions.

All such options have been tried. Several papers[1,2,3] have proposed field geometries which by holograms phase plates or what have you have been claimed to provide accelerations in violation of the general theorem given above. A more detailed critique of one[3] such proposal has been given by J.D. Lawson.[4] These mechanisms do not work.

I will now consider in turn some other proposed acceleration mechanisms that deviate from each of the assumptions.

II. Inverse Free Electron Laser (Wiggler Accelerator)

Assumption (2) is violated in "the interactions of relativistic particles and free electromagnetic waves in the presence of a static helical field."[5] Such interactions are the inverse of what has become known as a "free electron laser."

In this type of accelerator an alternating (or helical) static magnetic field causes the particles to follow an undulating (or spiral) trajectory (see Fig. 1) with wavelength (or pitch) = λ_H. The mean forward velocity of the particles v is given by

$$v = \beta c \cos\alpha$$

where α is the mean angle between the particle and the axis. Plane electromagnetic radiation is introduced traveling at velocity c in the same direction as the particles. The mismatch of velocities between the wave and the particle causes the apparent direction of the electric vector E to slowly oscillate (or rotate). The distance λp the particle travels for one complete oscillation (or rotation) is given by:

$$\lambda_p = \lambda/(1 - \beta \cos\alpha)$$

If now we set $\lambda_H = \lambda p$ then the direction of the electric field seen by the particle will follow the oscillating motion of the particle and continuous acceleration (a) or deceleration will result:

$$a = E_o \sin\alpha \sin\phi$$

where E_o is the maximum (magnitude) of the electromagnetic field and ϕ is the phase angle.

Unfortunately as the particles gain momentum then a given magnetic field B causes an ever smaller angle α and the acceleration (a) falls. In fact, it falls as the momentum to the 2/3 power. As a result the power P to attain a final energy g rises faster ($g^{2\ 2/3}$) than would be the case for more conventional fields (g^2). In full:

$$P \propto g^{2\ 2/3}\ \ell^{-1}\ B^{-2/3}\ \lambda^{1/3}$$

where ℓ = length of the accelerator. If we plug in numbers for a possible 1 TeV accelerator:

$$E = 1 \text{ TeV}$$
$$\ell = 300 \text{ m}$$
$$B = 10 \text{ Kg}$$
$$\lambda = 1\ \mu\text{m}$$

then $P = 2\ 10^{19}$ watts which is far more than the 10^{14} which is now available.

III. Inverse Čerenkov Effect[6]

In this case we deviate from the second assumption: we do not interact in a vacuum but use a gas with refractive index N to slow down the wave. Now if the particles and the light beam are at an angle θ (see Fig. 2) to one another, and if $\cos\theta = 1/N$, then the particles and the wave will remain in phase. The accelerating field a will be

$$a = E_o \sin\theta = E_o \sqrt{1 - \frac{1}{N^2}}$$

This effect has been experimentally observed.[7] The magnitude of E_o is, however, limited by gas breakdown, and this is worse if the pressure and thus N is greater. Although I know of no good study of possible gasses and pressures I have concluded that the highest attainable accelerations are of the order of

$$a \approx 100 \text{ MeV/m}$$

Although this is not higher than is possible with RF cavities it is perhaps worth pursuing the idea a little further. If $N \approx 1.02$ then $\theta \approx 16^o$ and $a \approx .2\ E_o$. If an axicon focus is employed then the laser power P is given by

$$P \text{ watts} \approx \frac{(E_o \text{ volts/cm})^2\ (\lambda \text{ cm})\ (\ell \text{ cm})}{840}$$

*Work performed under the auspices of the U.S. Department of Energy.

thus for a final energy g in eV

$$P \approx \frac{g^2}{\sin^2\theta \; \ell \; 840}$$

which for g = 1 TeV ℓ = 300 m, $\sin\theta$ = .1, λ = 1μ gives

$$P = 1 \; 10^{14} \text{ watts}$$

This is not unreasonable. The laser pulse energy J would depend on the pulse duration that could be arbitrarily small in principle and perhaps as short at 1 psec in practice. Then the pulse energy is:

$$J = 150 \text{ joules}$$

which is certainly small compared with the 40,000 joules needed in a "conventional" LINAC. Of course the low pulse energy implies that only small bunches could be accelerated; this, however, might be acceptable in some applications.

IV. Plasma Accelerator

The introduction of a plasma or high current electron beam into the region where the interaction takes place causes non linear effects that can then allow continuous acceleration. In particular, it has been shown[5] that the presence of a short pulse or wave packet of radiation passing through a plasma (or along an electron beam) will cause a change in the electron density in the region of the packet. This, in turn, forms a potential well in which positive ions or positrons are trapped and accelerated.

The change in electron density arises because the electromagnetic wave accelerates the electrons within it, carrying them along for a while, but finally returning them to rest. Consider, for example, the effect of a hypothetical packet as shown in Fig. 3. When the wave overtakes a particle at (a) the particle sees a sudden transverse field and is accelerated sideways. The field, however, also contains a magnetic field that if the field is strong enough curves the electron into a nearly forward direction. When the field changes direction (b) the electron is bent the other way and slowed till it is at rest at (c). It then starts another wiggle always advancing in the forward direction with some mean velocity $\beta_2 c$. The relation between this velocity and the electron density is illustrated in Fig. 4.

Consider a plane A-B at the center of the wave packet and advancing with it a velocity c. The rate that electrons are cut by this plane is $\rho c\,(1 - \beta_2)$; where ρ is the line density in the packet. This rate must be equal to the rate seen by the front of the packet which is $\rho_o\,(1 - \beta_1)$ where ρ_o is the line density outside the packet and β_1 is the velocity outside. For a plasma $\beta_1 = 0$ and

$$\rho = \rho_o \frac{1}{1 - \beta_2}$$

Clearly, as $\beta_2 \rightarrow 1$, ρ gets very large and will produce a deep potential well.

Recently,[9] this effect has been computer modeled for the plasma case with the addition of the electrostatic restraining forces that tend to disperse the high electron density and which cause plasma waves. When these effects are added and when the packet is short compared to the plasma wavelength then the resulting potential will be as shown in Fig. 5. There is now a plasma "wake" and now it is seen that electrons as well as positive particles can be accelerated.

The highest γ that an electron can be accelerated to in one pass is related to the wave velocity of the plasma and has been shown[9] to be:

$$\gamma_{MAX} = 2 \left(\frac{\omega}{\omega_p}\right)^2$$

thus to attain high energy one needs a low density (low ω_p) plasma. The maximum rate of acceleration then also falls. This undesirable characteristic may be avoided if multiple accelerating regions are used. Even with one region, however, high acceleration rates are possible. Table I shows the example given by Tajima and Dawson[9] and a second example extrapolated from the first for a 1 TeV final energy. It is seen that the gradient is 3 GeV/m which is excellent but the total laser power required is several orders of magnitude higher than the 10^{14} currently available.

Example	1	2
E max	1 GeV	1 Tev
ℓ	1 cm	300 m
N plasma cm^{-3}	10^{18}	10^{15}
λ	1 μ	1 μ
λ_p	30 μ	1 mm
t (packet length)	15 μ	.5 mm
I watts/cm^2	10^{18}	10^{18}
W watts	.6 10^{14}	2 10^{18}
J joules	3	3 10^6

V. Dielectric Tube

Our starting theorem does not apply near to electromagnetic sources because the waves corresponding to the "near field" from a source travel at velocities less than that of free radiation. Lawson investigated the near fields near dielectric surfaces and found, in particular, that acceleration was possible within a hole through a dielectric, providing that hole was of the order of a wavelength in diameter. Ignoring the difficulty of making such a hole he studied injection focusing, etc., but concluded that breakdown would limit the acceleration to a value of about 200 MeV/m or about the same as that in conventional LINACS or the inverse Čerenkov effect.

VI. Grating LINAC

Finally we come to the use of conducting structures very near to the beam. What we are really trying to do here is design a "conventional" LINAC whose scale is reduced to optical wavelength dimensions: a tube 30 μ diameter with drift irises every 10 μ would make a good LINAC for a CO_2 laser power source but is hard to make. We search for simpler structures that have the required properties which must, it can be shown, include a basic periodicity of the order of a wavelength. This was understood by Takeda and Matsui[11] in 1968 who proposed the simplest such periodic structure: a grating. It seemed obvious that it would work. The field seen by a particle far above a grating surface would alternately accelerate and decelerate the particle. But near to the grating the field would be "shorted out" when the particle was just above the ridges but seen as the particle passed a dip (see Fig. 6). The right choice of spacing should then assure continuous acceleration. The effect would appear to be the inverse of that observed by Smith and Parcell[12] in 1953. It was therefore a surprise, at least to this author, when in 1975 J.D. Lawson[10] showed that the acceleration as proposed decreased to zero as the particle velocity approached that of light.

It was not till 1979 that it was realized[13] that this failure of the grating LINAC to accelerate relativistic particles was, in fact, a quirk of the symmetry of the proposed geometry. If the light approaching the grating is not perpendicular to the grating but comes from the sides (e.g., Fig. 7) then the acceleration does not vanish and a practical grating LINAC can be designed.

In fact, it is found that a grating behaves in many ways like an accelerating LINAC. With no loss a standing wave can be formed above the grating that remains there as in a closed cavity without radiating off its power. With finite losses a Q can be defined for the grating and the accelerations obtained are then of the order of:

$$\text{Acceleration} \approx \sqrt{Q}\ E_{free}$$

Fig. 8 shows an actual solution with Acceleration 2.5 times the maximum free field that would be present at the same focus with no grating.

With such a grating accelerator the laser power presents no problems (as we shall see) but the need to avoid distruction of the grating will limit the maximum accelerations possible. Unfortunately, we have no real data on this limit and can only make guesses extrapolated from experience with diffraction gratings exposed to relatively long pulses. The field levels that can be tolerated will increase with very short pulses but here again we don't really know how short is possible. For a 30 psec pulse of 10 μ radiation, I estimated that 1 GeV/m should be possible. For 3 psec pulses 3 GeV/m might be all right. For an example, I will use this latter number which then gives the accelerator described below.

Energy	1 TeV
ℓ	300 m
P	$2\ 10^{13}$ watts
t	3 psec
J	60 joules

The real shock is the very low total energy of 60 joules, compared with 40,000 that would be used in a conventional wavelength LINAC 10 km long. The improvement is a direct consequence of the use of the short 10 μ wavelength.

A consequence is that per pulse very few particles can be accelerated (less than 10^8). However the power needed per particle need not in principle be any lower and, in fact, it can be shown (Appendix) that a single pass collider gives higher luminoisity for given power if a high frequency of very small bunches is used. So there may be no disadvantage here.

VII. Conclusion

To conclude, I would like to show Table III in which I compare 1 TeV examples of each of the accelerators I have discussed. Remember that the numbers have order of magnitude validity only.

Table III

	E/ℓ GeV/m	ℓ m	P Watts	J joules
Linac	.1	10,000	—	$4\ 10^4$
Černkov	.1	10,000	$2\ 10^{14}$	600
Dielectric	.2	5,000	$4\ 10^{14}$	1200
Wiggler	3	300	$2\ 10^{19}$	$2\ 10^7$
Plasma	3	300	$2\ 10^{18}$	$3\ 10^6$
Grating	3	300	$2\ 10^{13}$	60

Despite this reservation certain conclusions seem reasonable.

a) The inverse Čerenkov accelerator does not have much higher field gradients than conventional LINACS, but it does use far less energy and might be cheaper if low currents are acceptable.

b) The wiggler accelerator is not practical for high energies.

c) The plasma or modulated electron beam accelerators are a little more energy efficient than the wiggler but still far from practical for a 1 TeV machine. More work is, however, needed here.

d) The grating accelerator is still the most attractive alternative.

Appendix

Optimization of Luminosity/Power for Single Pass Colliders

Referring to the Amaldi[14] paper we obtain:

$$\begin{aligned} &\text{Luminosity} && L \propto f\ N^2/\sigma^2 \\ &\text{Power} && P \propto f\ \gamma\ N \\ &\text{Disruption} && D \propto dN/(\gamma\ \sigma^2) \\ &\text{Beamstrahlung} && \delta \propto \gamma\ N^2/d\ \sigma^2) \end{aligned} \qquad \text{(A1)}$$

where

- f = bunch repetition rate
- γ = final beam gamma
- N = particles/bunch
- σ = beam diameters at intersection
- d = bunch length

If I fix D and δ then

$$\begin{aligned} P &\propto L\ \gamma\ \sigma^{2/3} \\ f &\propto L/\sigma^{2/3} \\ N &\propto \sigma^{4/3} \\ d &\propto \gamma\ \sigma^{2/3} \end{aligned} \qquad \text{(A2)}$$

Clearly, P/L is reduced if σ, the beam size is reducad, but as we do this N and d <u>must</u> be reduced at the same time.

I now ask if there is any emittance problem as σ is reduced. Let ε be the specific emittance (particles per area per steradian at fixed γ). The spot size of a focus whose depth of focus parameter is β^* is then

$$\sigma = \sqrt{\beta^* \frac{\varepsilon N}{\gamma}} \qquad \text{(A3)}$$

I set $\beta^* = d$ since I cannot use a shorter depth of focus. Then

$$\varepsilon = \frac{\sigma}{N} \frac{\gamma}{d}$$

Using equations A2

$$\varepsilon \propto \frac{\sigma^2 \gamma}{(\sigma^{4/3})\ (\gamma\ \sigma^{2/3})} = \text{constant}$$

i.e., the specific emittance requirement is independent of σ or γ!

I conclude, therefore, that an improvement in luminosity to power ratio should be possible if super small bunches meet at super small spots. For the super small bunches laser accelerators are well suited.

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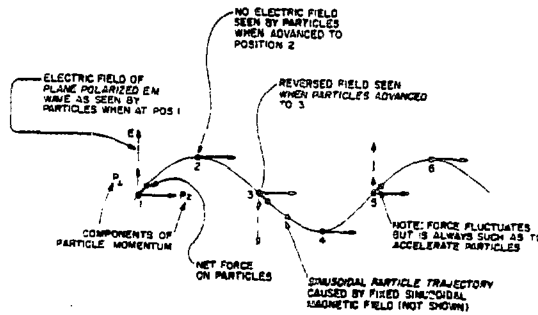

Fig. 1 Wiggler Accelerator showing forces on particles due to electromagnetic wave.

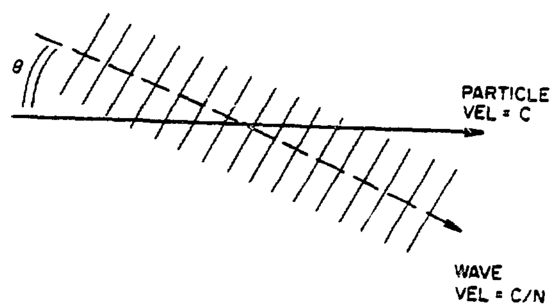

Fig. 2 Inverse Čerenkov effect accelerator.

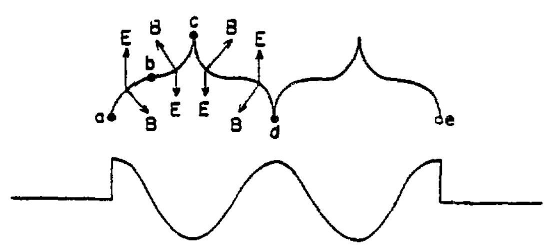

Fig. 3 Motion of free electron within a wave packet.

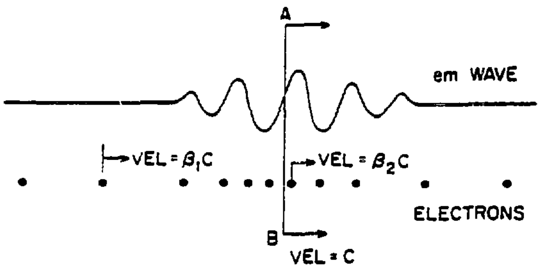

Fig. 4 Density effect of electrons within a wave packet. The wave packet field and electron positions are shown along the beam direction.

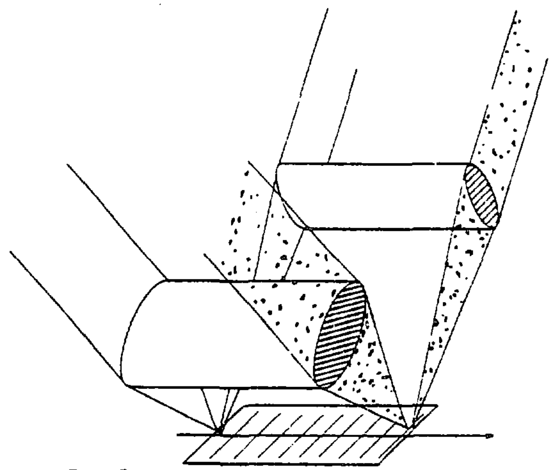

Fig. 7 Sideways grating accelerator geometry that does accelerate relativistic particles.

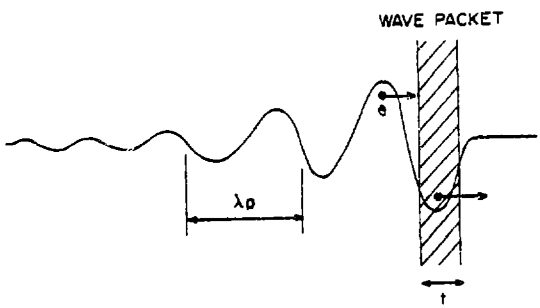

Fig. 5 Plasma wake accelerator. The electric potential is shown as a function of position along the beam direction.

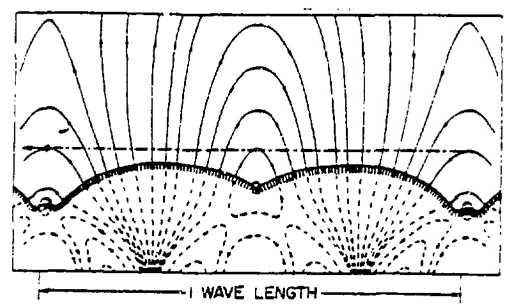

Fig. 8 Example of fields above a grating illuminated as shown in Fig. 7.

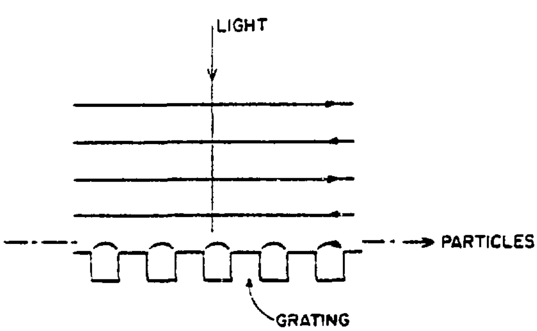

Fig. 6 Grating accelerator with light perpendicular to the grating. This concept does not work for relativistic particles.