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LASER ACCELERATORS

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Abstract

The use of lasers to accelerate particles to ultra-high energies is motivated by the very high electric fields associated with focused laser beams. A number of such schemes have been proposed: for example, microstructures driven by lasers operating in the optical-near infrared frequency range, laser-driven space charge plasma waves, inverse free-electron laser accelerator and the two-beam accelerator. Current status of these schemes is reviewed. Lasers may also find an application in improving the power sources and in focusing very high energy particle beams.

Introduction

It is well known that an extremely large electric field is produced when a short-pulse, high peak power laser beam is focused to a small spot. For the most powerful lasers now available, electric fields on the order of 10^{12} V/cm can be produced in the focal volume. It is natural to ask, therefore, whether such enormous fields can be used to accelerate particles to ultra-high energies in a short distance, thereby, miniaturizing a high energy accelerator. Several schemes have been proposed[1] and I shall review four of them. These schemes are not necessarily the most promising of the proposed laser acceleration schemes. I have chosen them because while these schemes have certain similarities they are sufficiently different from one another to be fascinating.

Although laser beams are very powerful, in free space they have an electric field that is transverse to the direction of propagation. A charged particle, therefore, cannot be accelerated to very high energies using the electric field of a laser. The motion of a charged particle in the combined electromagnetic field of a laser is depicted in Fig. 1. Because of the $\underline{v} \times \underline{B}$ force the particle is displaced, but sees no continuous acceleration and is in fact returned to rest after each cycle. In all laser acceleration schemes, therefore, some way must be found of allowing the particle to interact with the electric field of the same polarity for a long time.

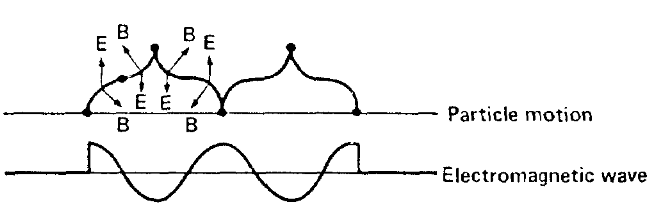

Fig. 1

Secondly, since an electromagnetic wave propagates at c in vacuum, it will always overtake a charged particle if the two are colinear. It is therefore necessary to slow the electromagnetic wave down so that its group velocity is slightly less than c. However, there is an ther option for increasing the wave-particle interaction. One can bend the particles continuously and periodically in a so called "wiggler" so that the particle traverses one wiggler period just as one period of the electromagnetic wave passes by the particle. This is the principle of the inverse free-electron laser accelerator

The third problem is that the colinear interaction between a laser beam and a particle is limited by the finite Rayleigh length of the focused laser beam. To get around this problem there are basically three options: to stage the accelerator, to keep laser beams focused over a length much greater than the Rayleigh length by using a waveguide or to use a laser to couple to an accelerating mode (in a cavity) at an angle. The acceleration schemes discussed in this talk use all three options.

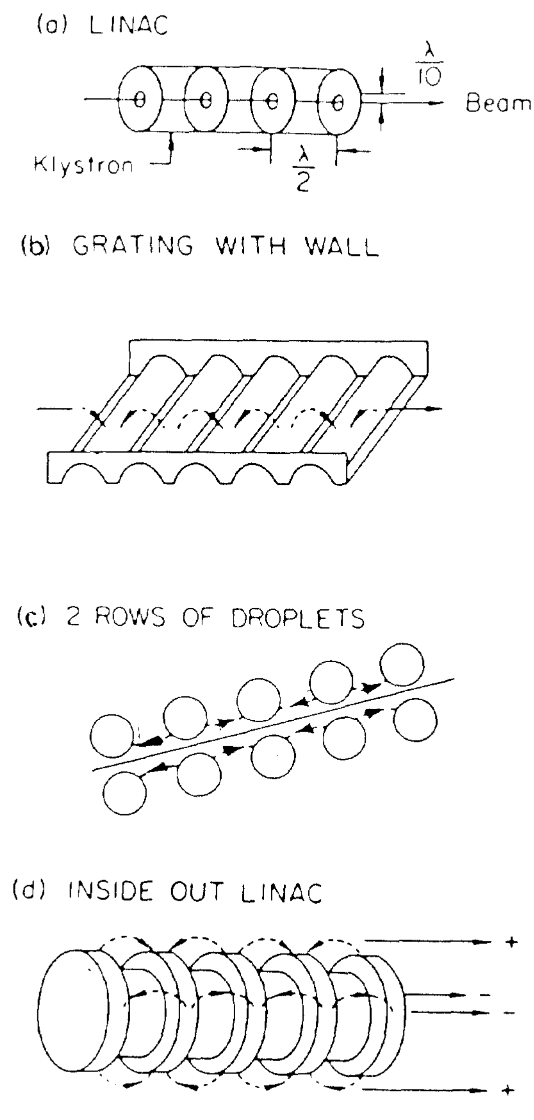

Fig. 2

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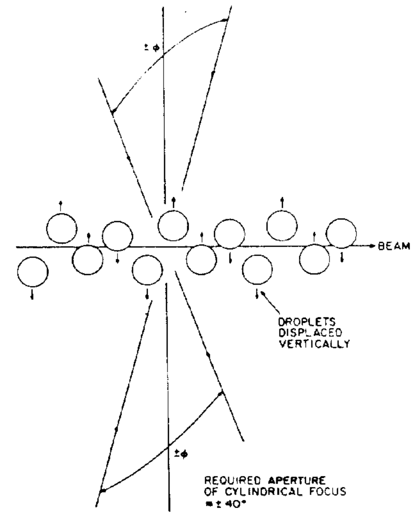
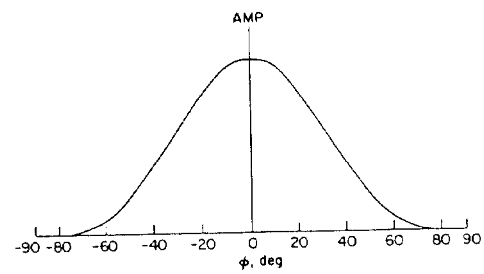
Laser Driven Microstructures

Conventional accelerating cavities consist of waveguides or transmission lines with the particles to be accelerated passing along the axis of such a structure. Fig. 2(a) shows a schematic of a conventional electron linac. In such a structure, a traveling electromagnetic wave is slowed down by the discs and provides an alternating field that is synchronous with the electrons. Typical accelerating gradients in such a structure are ~20 MeV/m at an operating frequency of 2.8 GHz. Recently, experiments have been carried out to see just what the maximum longitudinal field limited by surface breakdown is and it is thought that fields as high as 100 MeV/m may be possible.[2] At microwave frequencies the breakdown electric field scales as $\sqrt{f}$ while the energy stored goes down as f^2. In order to get higher fields therefore, one needs to work at still higher frequencies, and therefore a smaller structure size. This is indeed the principle motivation behind the "two-beam accelerator" to be discussed later. As one contemplates using even higher frequencies it becomes very hard if not impossible to construct the conventional slow wave structure. For instance, if we use e.m. radiation of $f \approx 30$ THz, the structure size becomes ~5 μm and one has to invent some sort of an open structure so that it can be fabricated and the radiation can be coupled to the structure easily from the outside. The motivation for going to such ultra-high frequencies is obvious. There are rather well-developed sources at this and still higher frequencies. For instance, very high power CO_2 (λ = 10 μm) and Nd: glass (λ = 1 μm) lasers have been developed for inertial fusion applications. Although laser sources needed for a TeV class accelerator will almost certainly exceed the capabilities of fusion lasers in the areas of pulse-width, repetition rate and the need for the power to be delivered in a single diffraction limited beam, fusion lasers easily exceed the necessary peak powers to test out some of the schemes described here.

The simplest form of a microstructure driven by a laser is a rectangular diffraction grating.[3] When such a grating is surrounded by vertical conducting walls[4] on the sides perpendicular to the grating lines, to prevent leakage of the radiation that is coupled from the laser to the cavity, then this structure behaves as an accelerating cavity with standing waves within the walls. This is schematically shown in Fig. 2(b). It has been suggested that instead of a grating, one can use rows of conducting droplets as a microstructure.[5] The microspheres have a radius of about 0.1 λ and are $\lambda/2$ apart as shown in Fig. 2(c). Considerable rf modeling has been carried out using 11 cm diameter spheres and 30 cm wavelength radiation in an effort to discover the suitable arrangement of the spheres to give a resonant accelerating mode which would have a high Q. Two rows of spheres are found to be a suitable arrangement. The spheres act as dipoles oscillating in the plane of the double row, 180° out of phase with one another. Particles can be accelerated along the axis between the rows where the electric field from the two rows reinforce each other. In order to couple the laser radiation in an actual droplet accelerator the microstructure has to be perturbed. This is equivalent to providing slots in a conventional cavity in order to couple radiation to it. It is found that if alternate spheres are slightly lifted or slightly depressed from the plane in which they initially lay, such a perturbation can couple the accelerating mode to radiation propagating either upward or downward perpendicular to the plane containing the spheres with an angular aperture of ~±40°. This is schematically shown in Fig. 3. A scheme for generating the rows of microspheres is currently under active investigation.[6]



Coupling to structures. Double droplet rows.



Angular distribution of radiation to or from droplet structure.

Fig. 3

Instead of using a grating with conducting side-walls one can wrap the grating on itself and obtain what amounts to an inside out linac.[7] Both electrons and positrons can be accelerated on different locations on the circumference where the field reverses its sign. This is shown in Fig. 2(d). Clearly, the crucial question is what are the maximum surface fields at these high frequencies before the surface melts or forms a plasma. Even for laser pulses that are only a few tens of cycles long, to the zero order one expects plasma to form when the quiver energy of the electrons in the material exceeds few times the work function. For a CO_2 laser this corresponds to $I \sim 5 \times 10^{11}$ W/cm^2 or an electric field greater than a GeV/m. The laser droplet accelerator does indeed envision using CO_2 laser pulses that are only a few picoseconds in duration. Such laser pulses have recently been generated and amplified to necessary power levels[8] but not to necessary energies or repetition rate but clearly potential exists for conducting preliminary experiments on this scheme.

Laser-Plasma Accelerators

The promise of ultra-high accelerating gradients is the main attraction of laser-plasma accelerators. These are collective accelerators where laser beams are used to excite a high γ_{ph} space-charge wave in a plasma. The longitudinal electric field associated with such a wave is simply proportional to $\sqrt{n_e}$ (cm^{-3}). Thus for plasmas with electron densities in the range $10^{16} < n_e$ (cm^{-3}) $< 10^{18}$, potential exists for obtaining maximum fields of $10 <$ E(GeV/m) < 100.

In the plasma accelerator scheme known as the plasma beat wave accelerator[9], (PBWA), two laser beams with frequencies and wavenumbers (ω_o, k_o), (ω_1, k_1) are injected into the plasma such that $\omega_o - \omega_1 = \omega_p$ and $k_o - k_1 = k_p$ where (ω_p, k_p) are the frequency and wavenumber of the space charge wave.

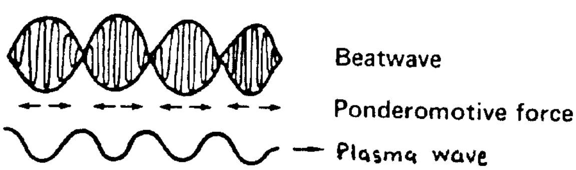


Fig. 4

The spatial intensity gradient of the beat wave envelope exerts a ponderomotive force on the plasma and gives rise to a plasma density wave which has a phase velocity v_{ph} that is equal to the group velocity of the light waves $v_g \simeq c(1 - \omega_p^2/\omega_o^2)^{\frac{1}{2}}$ (Figure 4). Extensive two dimensional particle simulations have been carried out to test the feasibility of the PBWA scheme.[10,11] It is found that provided that laser pulses on the order ten picosecond in duration are used, then a coherent plasma wave can indeed be set-up. In Fig. 5(a) we see a contour plot of two laser beams propagating through the plasma from left to right. Figure 5(b) shows the resultant contour plot of the plasma wave potential with alternate islands representing accelerating and decelerating buckets. Since the group velocity of the plasma wave is almost zero, a wake of plasma oscillations is left behind.

This wake eventually evolves into turbulence but the plasma wave within the laser envelope (which continually moves into fresh plasma) remains coherent and can be used to accelerate externally injected particles.

Recent experimental work[12,13] has shown that when 10.6 μm and 9.6 μm lasers with modest intensities($\sim 10^{13}$ W/cm^2)are injected into a 10^{17} cm^{-3} plasma, a space charge wave with $\gamma_{ph} = 10$ is indeed excited. The frequency, wavenumber and amplitude of the wave are measured using ruby laser Thomson scattering. The result is shown in Fig. 6. Figure 6(a) shows the frequency spectrum of the scattered ruby light. ω_r is the incident ruby frequency and frequency shifted by $\omega_p = \Delta\omega = \omega_o - \omega_1$ is the scattered peak showing the plasma wave. Figure 6(b) shows the angular spectrum of the scattered light which corresponds to the k spectrum of the plasma waves. This spectrum is found to peak at $\Delta k = k_o - k_1$ as expected. The measured amplitude of the plasma wave was in the 300 MeV/m-1 GeV/m range compared to the expected amplitude of ~2.8 GeV/m. This is the first conclusive demonstration of controlled excitation of very large electric field in a plasma which may one day be used to make a practical accelerator.

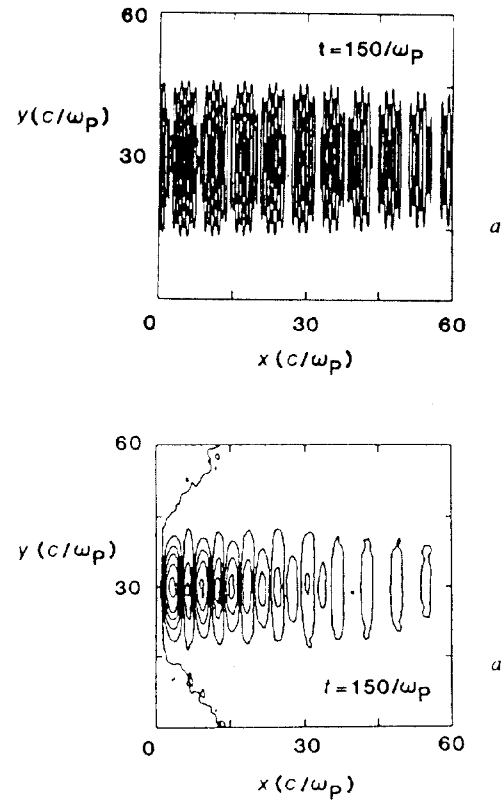


Fig. 5

Since the phase velocity of the plasma wave in the PBWA is somewhat less than c, relativistic particles will eventually overtake the wave. One then has to stage the accelerator or phase-lock the particles in the accelerating bucket. It is found that by applying a transverse B field to the plasma wave, particles can not only be phase-locked but bunched at one phase-stable point.[14] The double beat wave configuration[15] is yet another inventive suggestion for alleviating the problem of particles outrunning the beat-wave. In all these schemes laser beam depletion eventually limits the acceleration length.

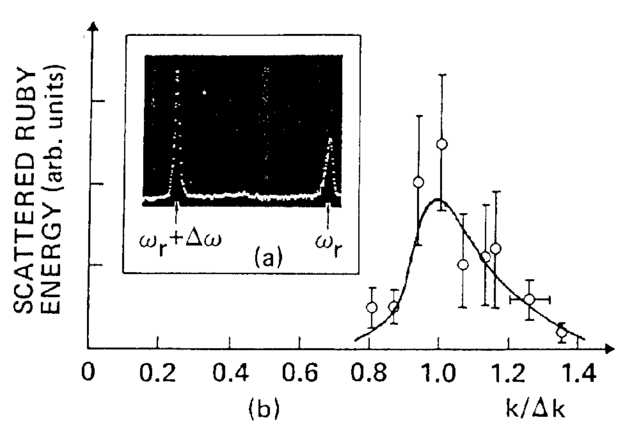


Fig. 6

To get around the difficulty of replenishing the laser beams a side injected scheme has been proposed.[16] This has many similarities with the plasma-droplet accelerator[17] where the droplet spacing is λ (i.e. non-resonant). Instead of having discrete ionized micro-spheres as in the plasma-droplet scheme, in this scheme sinusoidal ion density perturbation having periodicity of λ is set-up. The laser beam (only single frequency) can now be brought in transversely and couple to a surface wave which runs along the k of the ion perturbation.

Although the topic of this talk is laser accelerators, I will mention one recent important development in the plasma accelerator area which involves not laser drivers but a relativistic particle bunch as a driver. The energy density in electron bunches is comparable to or exceeds that in the most intense lasers. Furthermore, electron bunches can be generated more efficiently than laser pulses. When an appropriately shaped bunch of electrons is injected into the plasma it leaves behind a "plasma wake" which can be used to accelerate another bunch of lower density electrons to higher energies.[18] This scheme is analogous to other wake field acceleration schemes [19,20] except a plasma is used rather than an RF structure to excite the wake. Even in colinear arrangement where the trailing bunch follows the driving bunch, a transformer ratio of greater than 2 and perhaps up to 10 appears achievable.[21]

Inverse Free Electron Laser Accelerator[22,23]

In contrast to the plasma accelerators the inverse free electron laser (IFEL) acceleration mechanism is inherently simple in that it does not rely on collective effects. It works as follows: the combined action of the laser (ω_o, k_o) and a static wiggler field (o, k_w) on the electrons result in a ponderomotive wave. The ponderomotive wave has a phase velocity slightly less than c since $v_{ph} = \omega_o/(k_o + k_w) = c/(1 + k_w/k_o)$. This ponderomotive well can trap and continuously accelerate electrons. However, in order for this to happen the resonance condition which relates the electron energy to the wiggler and laser parameters must be maintained. This is given by $\gamma_R = (1 + a_w)^{1/2}(\lambda_w/2\lambda_o)^{1/2}$. Here $a_w = eA_w/\ m_oc^2$ where A_w is the vector potential. It can be seen that as γ increases either a_w and/or λ_w must both increase; we need a tapered wiggler. Unfortunately a_w cannot be increased too much because since the electron beam is being bent continuously there is radiation loss. It has been suggested that by adding a gas to the IFEL accelerator cavity one can reduce the synchrotron radiation loss by modifying the resonance condition so as to allow larger values of λ_w.[24] It appears, however, that synchrotron emission will be the eventual limitation on the maximum energy that can be obtained from an IFEL accelerator.

A schematic representation of an IFEL accelerator is shown in Fig. 7. The wiggler, laser and electron beam parameters have been computed for a single-stage IFEL accelerator to accelerate electrons to 5 GeV energy. These are given in Table 1. It can be seen that, more than that for any other acceleration scheme described in this paper, technology exists for building such a prototype accelerator. For propagating the laser beam over a distance much greater than the Rayleigh length the use of a metallic waveguide has been suggested.

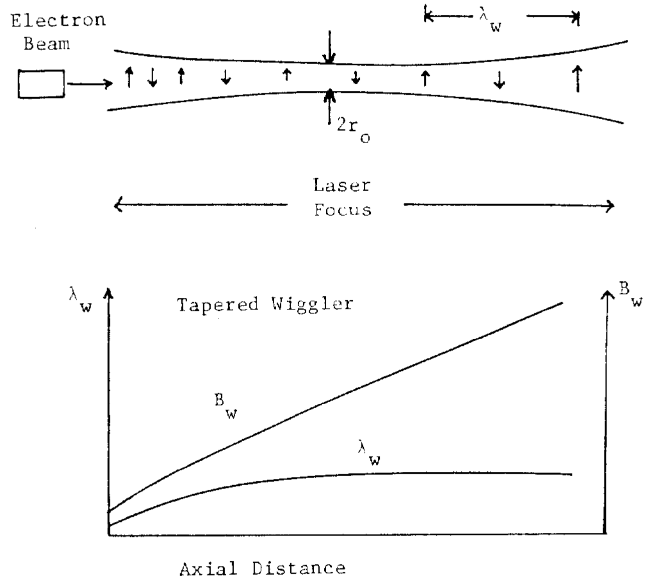


Fig. 7

TABLE 1

Single-stage 5 GeV IFEL parameters[25]

Laser Parameters	
Power	2×10^{13} W
Pulse length	1 ns
Spot size	3.5 mm
Wavelength	1 μm
Laser field	2×10^{10} V/m
Acceleration length	39 m
Wiggler Parameters	
Field amplitude	2-50 kG
Wavelength	2-10 cm
Electron Beam Parameters	
Initial energy	50 MeV
Final energy	5.3 GeV
Current	< 2 kA
Beam radius	2 mm
Average gradient	120 MeV/m
Beam displacement	0.5 mm
Energy spread	0.05%

Two-Beam Accelerator[26,27]

The two-beam accelerator (TBA) is not in a true sense a laser accelerator because the electrons are accelerated, not by radiation in the optical frequency range, but by high frequency microwaves from a free electron laser (FEL). The stored energy and the power needed to overcome resistive losses in a conventional linac scale as square of the accelerating gradient. In the microwave regime since the breakdown field scales as $\sqrt{f}$ and the stored energy goes down as f^2, it is worthwhile to operate at higher frequencies than 2.8 GHz of SLAC. There are a number of possible power sources in the 30 GHz range such as photo-cathode klystrons and the FEL.

The TBA is so called because it used an intense low energy electron beam to generate high frequency radiation by the FEL mechanism. A schematic of an FEL is shown in Fig. 8. In an FEL a relativistic electron beam (primary beam) is sent through a

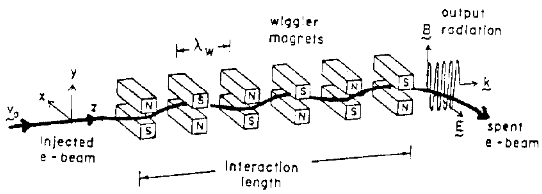


Fig. 8

periodic, static, transverse magnetic field or a wiggler. The magnetic field bends or wiggles the electrons continuously and periodically. Since the electron path is now sinusoidal, an electromagnetic wave can be made to overtake the electron beam by one wavelength as the beam traverses one wiggler period. This causes the radiated emission from the electron beam to be coherently amplified.
Recent experiments have shown that high power microwaves at f = 34.6 GHz can indeed be generated by the FEL process.[28]

In a TBA, the microwave radiation generated by the FEL is coupled through the directional couplers to a miniature but conventional high gradient slow wave structure (Fig. 9) and used to accelerate a compact bunch of electrons (secondary beam) to high energies. As the primary beam gives up its energy to amplify the microwaves, it is depleted and, therefore, must be replenished periodically using induction units. Fortunately, induction accelerators are quite efficient and, therefore, the transformer efficiency can be quite high. In Fig. 10 a side view of the FEL with periodically distributed induction units is shown. Average acceleration gradients of 250 MV/m appear quite possible at these frequencies. Experimental work to study the break-down limits, coupling of the microwaves to the high energy beam and fabrication problems associated with constructing a small-bore accelerating structure is being persued at present.[29]

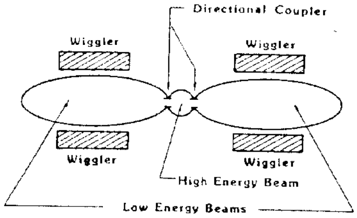


Fig. 9

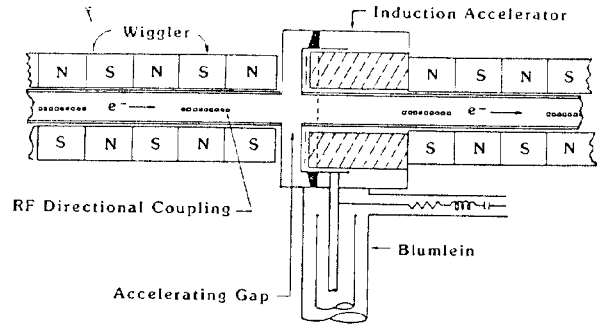


Fig. 10

Other Laser Acceleration Schemes

A) Inverse Cherenkov Acceleration:[30,31] If a laser beam is propagated in a gaseous medium such as hydrogen at 1 atmosphere (which has a refractive index slighly greater than unity, $n-1 = 10^{-4}$) then it can resonantly interact with a relativistic particle at the Cherenkov angle θ_c given by $\cos\theta_c = 1/n\beta$.
If β and $\cos\theta$ do not change, the fields seen by the particle remain constant in time. The particle sees an electric field $E \sin\theta \cos\psi$ which either accelerates or decelerates the particle depending on the sign of the phase angle ψ. The maximum electric field in the gas is limited by laser breakdown of the gas which for picosecond 1 μm laser pulses and 1 atmosphere may be on the order 100 GeV/m making this scheme interesting for producing accelerating fields on the order 1 GeV/m.

B) Two-Wave Accelerator:[32,33] The principle of the two wave accelerator is similar to that of the IFEL accelerator except now instead of a static wiggler, a microwave field propagating at a small angle with respect to the particle beam is used to oscillate the particle. As the particle energy changes, either the phase or the angle at which the microwave "wiggler" propagates has to be adjusted to maintain resonance. It has recently been shown that the two-wave accelerator can be improved by employing three waves[34].

Laser Driven Photocathodes

It has long been realized that lasers may find an application in producing very high quality electron sources of variable frequency. When a photocathode is irradiated by a pulsed laser, precisely timed and even temporally shaped electron pulses can be generated. Since the response time of a photoemitter is sub-picosecond, photocathodes driven by picosecond laser pulses can give low-emittance, high-current and even polarized bunches of electrons. Such electrons bunches, when accelerated/ decelerated in a conventional RF structure may find applications in

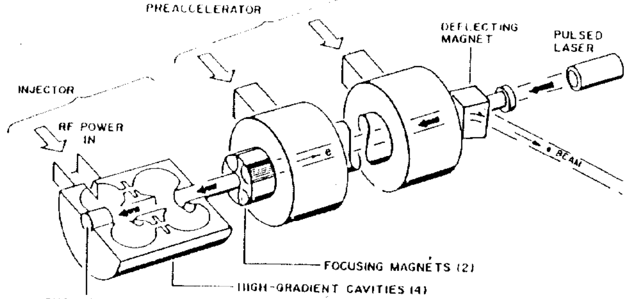


Fig. 11

FEL's operating in the UV[35], wake field accelerators[36] and improving the power sources[37].

A conceptual design of an electron injector based on the use of an rf-photocathode gun is shown in Fig. 11. A mode-locked laser is used to generate electron bunches less than 50 ps in duration and carrying a charge of up to 10 nC. The repetition rate is around 100 MHz. The photoemitter is placed on the end wall of an rf cavity in which the longitudinal field is ~30 MV/m. The resulting rapid acceleration reduces the time in which space-charge forces can act to degrade the emittance.[38] The goal for photoemitter guns is to produce currents in the 100 amp range with normalized emittance of ~10π mm mrad.

Laser Focusing

In a high energy collider, the accelerated particles must eventually be focused to an extremely small spot size at the collision point. It has been suggested that extremely strong laser lenses can be developed to do this focusing[39]. One such scheme utilizes the inverse Cherenkov effect, mentioned earlier, to focus particles and has the potential of high focusing gradients (~200 kG/m) and rapid and accurate control of the focusing element. The focal length of a lens of length L, for a particle with relativistic factor γ, subject to laser light of wavelength λ and power P is given by

$$f = (2.3 \times 10^3) \frac{\gamma \lambda^{3/2}}{\theta^3 L^{\frac{1}{2}} P^{\frac{1}{2}} \sin\psi} \text{ (mks units)}$$

where θ is the Cherenkov angle. For example with θ= 52 mrad (hydrogen at 10 atmosphere), $\lambda = 10^{-5}$ m, $\gamma = 10^5$, $L = 10^{-2}$m and $P = 10^{10}$ W we have

$$f = 5.3/\sin\psi \text{ meters.}$$

Depending upon $\sin\psi$ we can obtain either a +ve or a -ve lens. For beams unbunched at the laser wavelength $\sin\psi$ varies from -1 to 1 resulting in all the possible positive and negative values of the focal length f. It has been observed that a positive focusing effect can be obtained for all ψ's by using a succession of lenses phased so that ψ of the particle increases by $\pi/2$ between lenses.

Conclusions

In this paper we have reviewed the current status of four "laser" acceleration schemes. Considerable progress has been made in the last two years in understanding the physics of these schemes and suggestions for specific experiments have emerged. Experiments on the PBWA have already demonstrated gradients of up to 1 GeV/m and FEL's have been shown to be capable of generating very high power microwaves. High power picosecond CO_2 laser pulses necessary for conducting experiments on microstructures and plasma accelerator schemes have been produced. Although the success of any of these schemes in making a practical accelerator cannot be predicted, it is certain that intense activity in this field will increase our understanding of the parameter space not thoroughly explored by accelerator physicists.

Acknowledgments

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