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TRANSVERSE PARTICLE ACCELERATION TECHNIQUES USING LASERS AND MASERS

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Introduction

The development of compact, high energy electron accelerators will provide an essential component for many new technologies, such as high power free electron lasers, X-ray and VUV sources, and high power millimeter and microwave devices. Considerable effort has been directed toward studies of new concepts for electron acceleration, including inverse free electron lasers[1,2], GYRACS[3,4,5] and modified betatrons[6,7]. Most of these conceptual devices require high external magnetic fields and/or complicated injection devices. The concept to be discussed herein uses an intense traveling electromagnetic wave, produced by a laser or maser source, to accelerate electrons in the Rayleigh region of a focused beam. Although the possibility of non-synchronous acceleration has been considered[8], very little analysis of potential device configurations has been reported. Computer simulations of the accleration process indicate practical figure of merit values in the range of 100 MeV/m for achievable electric field strengths with current technology.

Analysis

A schematic of the basic concept is shown in Figure 1. A laser beam with near diffraction limited performance is brought to a focus near the electron injection region. Depending upon the laser pulse length, electrons are injected into the focal region prior to or during the laser pulse. The intense electron beam can be provided by a field emission diode or similar high current source, with very few restrictions on the phase space configuration of the electron beam. The injected electrons are rapidly accelerated by the ponderomotive force of the laser traveling wave, and are accelerated to several hundred MeV within the Rayleigh range of the laser beam. The behavior of a single electron in an intense uniform circularly polarized traveling wave is shown in Figure 2, with electric field strength levels at 6×10^{13} V/m for 0.55 μm laser light. Note that the particle orbit is periodic in one coordinate and linear in the other two. The lateral drift is a result of the abrupt turn-on of the fields in this case. The electron reaches a peak energy near 100 MeV in the order of 30 μm before any deceleration begins. It is thus essential that the laser fields be "turned-off" after the electron has reached peak energy. This is accomplished in effect by the beam itself, as the high field strengths only exist in the Rayleigh region near the laser beam focal plane, as defined in Figure 3.

The peak electron energies attainable as a function of the wavelength of the driver radiation and the electric field strength (i.e., power density) of a uniform circularly polarized traveling wave were determined in a parametric analysis. The scaling behavior is shown in Figure 4, with a quadratic dependence of peak energy on the electric field strength evident for constant wavelength. For a given peak acceleration value, the necessary electric field strength scales as the inverse of the wavelength. This means that at longer wavelengths lower power densities are required; however, due to diffraction effects lower power densities are a result of the larger minimum beam waist size at the focal plane. The net result of the scaling and diffraction effects are such that to first order there is no optimum wavelength for acceleration. However, the larger the focal region, the more charge that can be accelerated. The scaling evident in Figure 4 is a result of electron acceleration from zero initial velocity. If the electrons have an initial axial velocity in the direction of the traveling wave, then the particle and wave phase velocities are closer in value and the acceleration process can continue in the proper phase for a longer time before phase slippage, thus producing higher peak energy values. This is shown in Figure 5 for various values of β_{11} with 0.55 μm radiation and 6×10^{13} V/m field strengths.

Previous data shown assumed a uniform field distribution in the focal region. A uniform field would quickly result in a deceleration of the electrons in a short distance. A more realistic model was utilized to demonstrate the practical aspects of this concept which utilizes the variation in field strength to prevent electron deceleration. An adiabatic approximation was used for the axial variation of the electric and magnetic field vectors, as well as an exponential radial distribution. The axial field variation and the subsequent acceleration levels are shown in Figure 6 for 0.55 μm light. Note that the electron attains a significant fraction of the maximum allowable energy and exits the focal region before any significant deceleration can occur.

One of the important features in any practical accelerator device is the nature of the charge injection process. The two obvious configurations for electron injection are axial and transverse to the laser beam. Consider transverse injection requirements first. If a circularly polarized electromagnetic wave is used, then transversely injected electrons will be reflected from the high field focal region before appreciable acceleration can occur. Transverse injection can be used if the wave is linearly polarized, and electrons are injected normal to the plane of the electric field vector. The sensitivity to velocity components parallel to the electric field will determine the fraction of the electron beam which is accelerated. Figure 7 shows the time history of an injected electron for a linearly polarized wave with an adiabatic axial variation and an exponential radial distribution in the electric field strength. No attempt was made to optimize the acceleration process. It should be noted that if a series of very short (picoseconds) laser pulses are used, then electrons can be injected into the acceleration volume before the pulse

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arrives, thus eliminating many restrictions on the emittance of the electron beam. Axial injection at or near the focal plane will allow circularly polarized beams to be used and higher energy levels to be reached. However, axial injection is more complex from a design standpoint, since provision has to be made to allow the laser beam to pass through the electron source, or vice versa. Again, care must be taken to prevent particle reflection similar to magnetic mirror effects. Injection prior to the pulse arrival can obviate some of the problems encountered in axial injection.

Some speculative concepts for laser-driven accelerators are shown in Figures 8a thru 8c. Injection within a laser resonator, as in Figure 8a, can provide higher field strengths by eliminating outcoupling losses. Axial electron velocity may provide preferrential acceleration by one of the traveling waves; if not a ring laser configuration may be necessary to select the proper wave direction. If a short pulse laser is used, a means of recirculating the laser pulse would increase the average accelerated current, as in Figure 8b. Finally, the laser beam can be refocussed to provide multiple acceleration regions, as in Figure 8c.

As mentioned previously, this acceleration concept will work in the microwave regime with lower field strengths. Figure 9 shows some performance curves for a uniform circularly polarized maser beam. These power levels may be accessible using TEM mode resonator cavities. Note that the use of an axial external magnetic field (GYRAC configuration) may allow improved performance at lower fields for the microwave regime.

Conclusions

A preliminary investigation of a concept for accelerating electrons using traveling electromagnetic waves in a vacuum environment has been presented. Energy levels of the order of 100 MeV can be attained in distances of the order of several Rayleigh lengths, although practical limitations on source size and extraction devices will limit figures of merit to the order of 100 MeV/m. The primary challenge to designing high power devices will be to devise ways to increase the volume of the acceleration region and/or the repetition rate of the device so as to increase the output current. More accurate models for the time history of electric and magnetic field vectors in the focal region are also needed to determine more carefully the limits on the electron injection process. Nonetheless, the simplicity of the acceleration process should provide the impetus for the develoment of these devices.

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Figure Captions

Figure 1. Schematic of basic concept

Figure 2. Single particle orbit under the influence of a 6×10^{13} V/m electric field vector of a 0.55 μm laser beam

Figure 3. Definition of the Rayleigh region

Figure 4. Peak electron energy as a function of the electric field strength for various radiation wavelengths. A uniform circularly polarized plane wave was assumed for the driver field.

Figure 5. The variation of the peak electron energy as a function of the initial axial velocity for a uniform circularly polarized wave with 6×10^{13} V/m field strength.

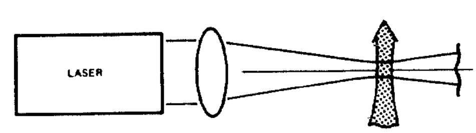
Figure 6. The dashed curve is a simulation of the variation of the magnitude of the electric field strength in passing thru the focal region (peak value of 6×10^{13} V/m). The plane wave geometry was assumed to be valid, i.e., there are no z components to the electric and magnetic fields. The radial profile assumed was of the form $e^{-(r/r_0)^2}$ with $r_0 = 8$ μm and the electron had an initial velocity $\beta_z = 0.1$. The solid curve shows the energy gain as a function of axial position relative to the electric field axial variation.

Figure 7. Electron injection orbit for a spatially varying laser beam in a direction normal to the plane of polarization of the wave electric field vector.

Figure 8. Several possible configurations for a laser accelerator are shown.
(a) Injection internal to the laser cavity
(b) Multiple pass or multiple pulse ring configuration
(c) Multiple electron beams from a common pulse which is periodically refocused.

Figure 9. Representative peak energies attainable (assuming a uniform circularly polarized plane wave) at microwave frequencies. The dashed curve shows additional energy gained by using an axial static magnetic field.

FIGURE 1



LASER ACCELERATOR SCHEMATIC

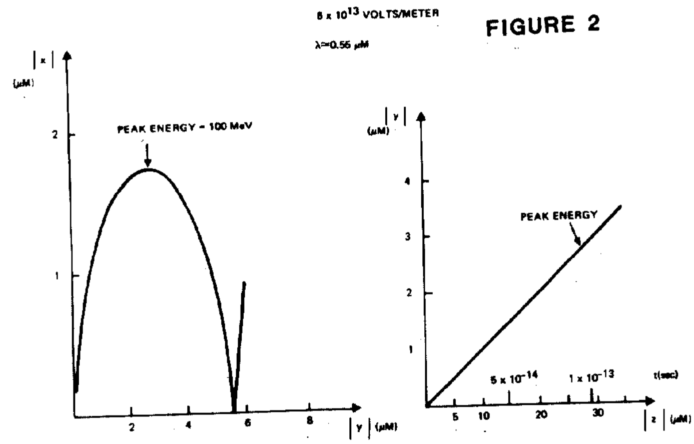


FIGURE 2

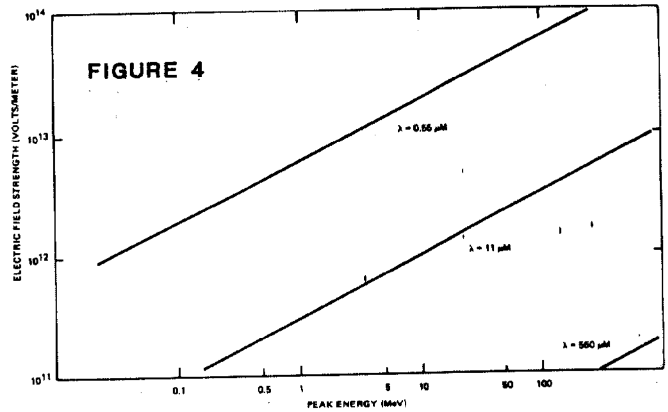


FIGURE 4

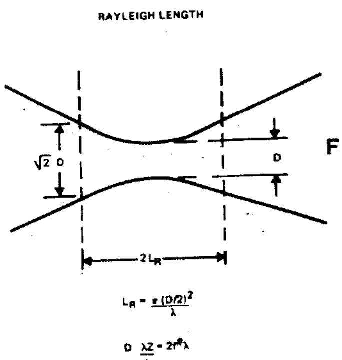


FIGURE 3

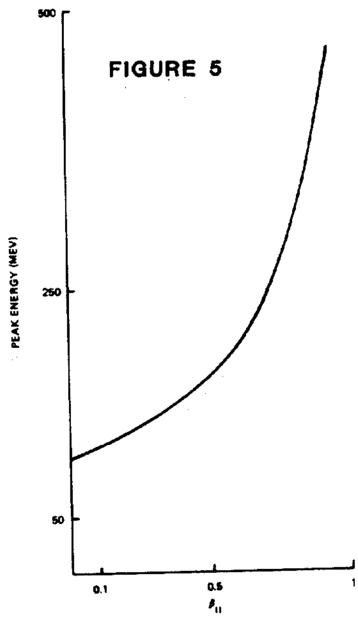


FIGURE 5

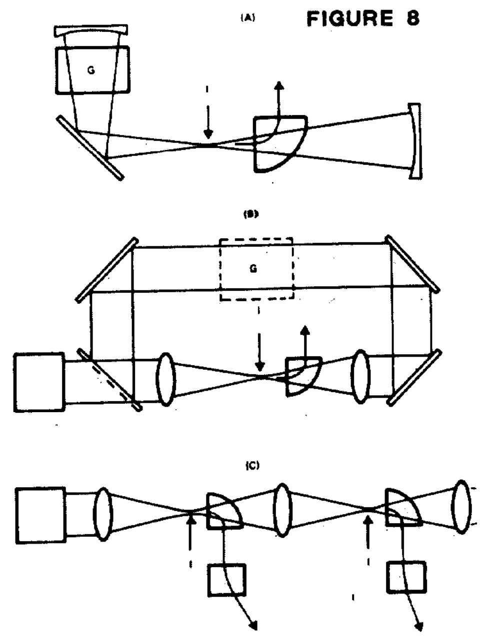


FIGURE 8

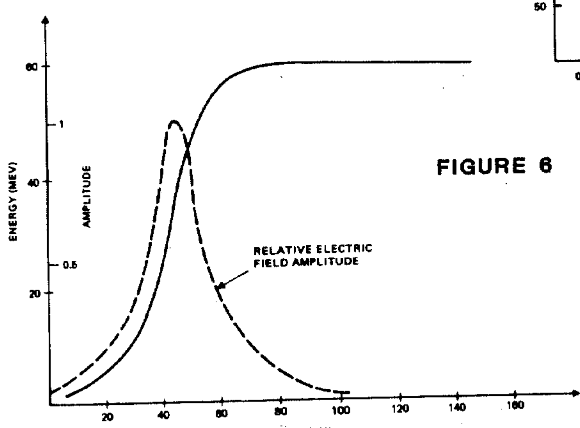


FIGURE 6

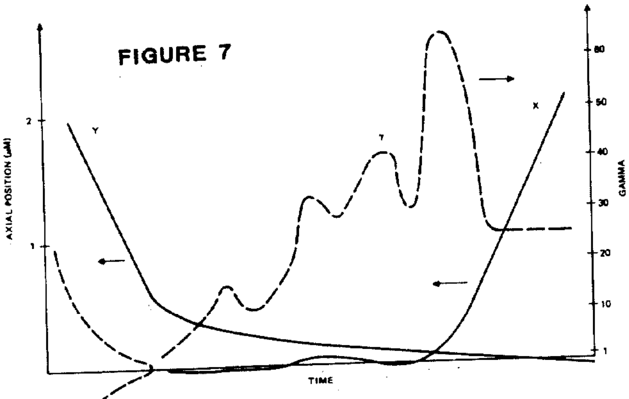


FIGURE 7

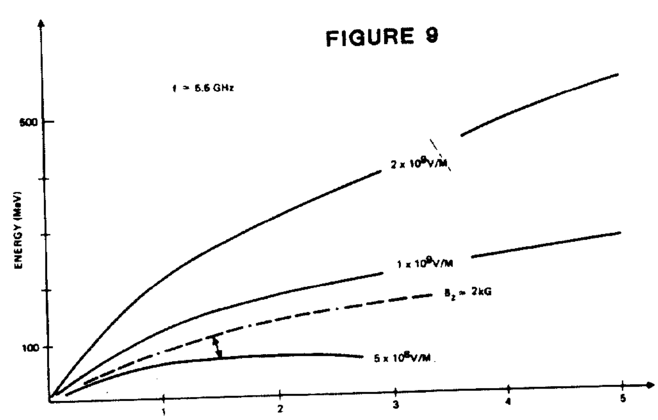


FIGURE 9