A New Look at Inverse Čerenkov Acceleration and Vacuum Laser Acceleration*

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Abstract

Two new approaches for inverse Čerenkov acceleration (ICA) and laser acceleration in a vacuum are presented. The improvement for the ICA process is to use reduced gas pressure (say ≲0.01 atm), but operate with the laser wavelength near a natural resonance of the gas, thereby maintaining the necessary index of refraction. For the vacuum laser accelerator the idea is to utiltize the same optical system as used during ICA (i.e. radially polarized laser beam focused by an axicon), but without a gas. The phase slippage between the electron and light wave can be limited, thereby ensuring that the oscillatory EM wave does not cancel out any net acceleration. In both schemes, acceleration gradients of several GeV/m appear possible.

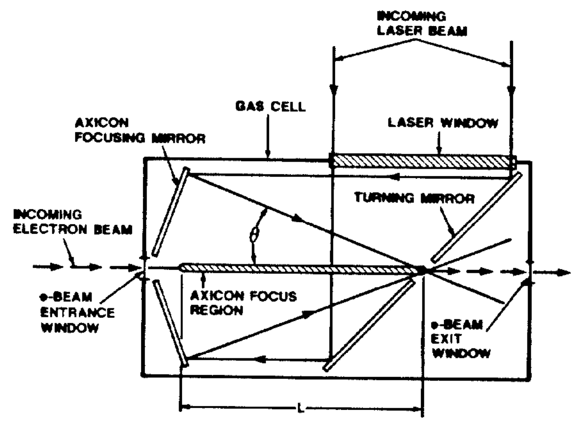

Figure 1. Plan view of inverse Čerenkov acceleration configuration.

I. INTRODUCTION

Inverse Čerenkov acceleration (ICA), in which a phase matching gas is used to slow the phase velocity of the laser light with the electron, has been experimentally demonstrated [1] as one possible approach for laser acceleration. An improved configuration has been proposed [2] which utilizes a radially polarized laser beam focused onto the *e*-beam using an axicon. This configuration is shown schematically in Fig. 1. Preparations [3] are currently underway to test this configuration on the Accelerator Test Facility (ATF) at Brookhaven National Laboratory.

Due to problems with electron scattering off the gas molecules and phase mismatch caused by the acceleration process [4], ICA is most attractive in the role as an energy booster for electrons whose energies are already ≳1 GeV. Acceleration gradients of >1 GeV/m are possible assuming the peak powers available from lasers today.

The low Z of H_2 reduces the effects of scattering and makes it a good phase matching medium, but even when accelerating 1 GeV *e*-beams to, say, several TeV there can be appreciable *e*-beam emittance growth introduced during the process. To minimize this effect the gas pressure needs to be as low as possible, but this also reduces the index of refraction n of the gas. One way to overcome this situation is to select a laser wavelength λ near the natural resonance λ_a of the gas molecules. Then, due to the dispersion of the medium, n can still be relatively large even at low gas densities. This is the basic strategy for the near-resonance ICA process described in Sec. II.

Ideally, the best way to eliminate any *e*-beam emittance growth is to remove the gas entirely. This, of course, means there can no longer be any phase matching between the electron and light wave velocities. Indeed, this is no longer an ICA process; however, the radially polarized laser beam/axicon focusing configuration provides important advantages for laser acceleration in a vacuum. This idea is presented in Sec. III.

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II. NEAR-RESONANCE ICA

A. Review of Analysis

The near-resonance ICA process has been analyzed in detail in Ref. [5]. Hence, the results will only be briefly summarized here.

There are several effects that occur when operating an intense laser beam near the resonance of a gas. These are: absorption of the laser light, saturation of the media, group velocity mismatch with the phase velocity of the light (to which the electron velocity is matched), and dispersion of the laser pulse. Given λ_a, these effects combine to determine an optimum value for λ. The optimum acceleration gradient goes as

$$\frac{dW}{dz} \sim \left(\frac{P_L}{L\,\tau_L}\right)^{1/4} N^{1/2}, \qquad (1)$$

where P_L is the laser peak power, L is the interaction length, τ_L is the laser pulse length, and N is the gas pressure.

B. Sample Results

A couple of examples are given here (see Ref. [5] for more). If the gas is NH_3 with other parameters as follows: N = 0.01 atm, f_r = 0.077, λ_a = 0.20 μm, λ = 0.248 μm (KrF laser), and P_L = 1 TW, then dW/dz = 0.8 GeV/m. For this preceding case λ is not optimum; in the next example λ is optimum. If the gas is Li with other parameters as follows: N = 0.01 atm, f_r = 0.75, λ_a = 0.67 μm, λ = 0.8 μm (Ti:sapphire laser), and P_L = 1 TW, then dW/dz = 5.4 GeV/m. Thus, under optimum conditions but using realistic parameter values, very high acceleration gradients are possible.

The *e*-beam emittance growth during ICA increases directly with the gas pressure [4]. ICA experiments thus far [1],[3] operate at gas pressures of order 1 atm. Hence, being able to operate at 1/100 atm would reduce the emittance growth in these experiments by approximately the same amount (corrections for the higher scattering cross sections of molecules, such as NH_3, must also be included).

III. LASER ACCELERATION IN VACUUM

A. Background

The possible laser acceleration of relativistic electrons in a vacuum has been extensively analyzed in the past [6]-[7], but has always faced fundamental limitations. Two primary ones are that the electric field distribution is extremely complex in the focal plane of a linearly polarized, focused Gaussian beam and has significant transverse field components [7], which will tend to deflect the particles and increase the beam emittance. Second, the interaction length must be limited [8] so that the oscillatory EM field does not cancel out any net acceleration.

We have found that these two problems can be overcome by using the radially polarized laser beam focused by an axicon geometry developed for ICA, but without any phase matching gas. The radially polarized beam focused by the axicon provides not only a longitudinal electric field component for accelerating the particle, but also axisymmetric transverse field components that can help focus and channel the *e*-beam. Also, the axicon does not focus the laser beam onto a point on the *e*-beam axis like a regular lens does, rather it creates a line focus along the *e*-beam axis. This means the angle that the laser light intersects the axis is independent of the length of the line focus (i.e. the interaction length). Consequently, the interaction length can be adjusted to control the amount of phase slippage between the electron and the light wave. In a point focus this is not possible because of the fundamental relationship between the focusing angle and the Rayleigh range.

It is important to emphasize that this scheme is not ICA because it does not attempt to phase match the velocity of the particle with the light wave. Instead, the particle is allowed to slip over the phase of the light wave. As long as this slippage is limited to less than π the particle will experience net acceleration.

Fundamentally, this scheme is analogous to microwave accelerators where electrons are accelerated by the traveling wave of the microwaves in cylindrical waveguides. As the electron is accelerated and slips out of phase with the microwave it enters a new waveguide section and the acceleration process repeats itself. In our case the "waveguide" is provided by the line focusing properties of the axicon. The interaction length or "waveguide" length tends to be limited to a few centimeters, but like conventional microwave accelerators these short lengths can be staged in series to achieve large final electron energies.

B. Review of Analysis

A detailed analysis of this new vacuum laser acceleration concept is presented elsewhere [9]. The results are summarized here.

To maintain positive acceleration, the interaction length L must be limited to

$$L = \frac{\Delta\phi}{\pi}\frac{\lambda}{\theta^2}\left(1 + \frac{1}{\gamma^2\theta^2}\right)^{-1}, \qquad (2)$$

where $\Delta\phi/\pi$ is the amount of desired phase slippage, θ is the intersection angle between the e-beam and the laser beam, and γ is the relativistic parameter. For an axicon, L is given by a_o/θ, where a_o is the radius of the laser beam. Hence, L can be selected by varying either a_o or θ.

Once L is determined by choosing a value for $\Delta\phi/\pi$, then the net energy gain ΔW over L is given by

$$\Delta W\ (\text{eV}) \cong 64.9\left(\frac{\Delta\phi}{\pi}\right)^{1/2} P_L^{1/2}\ (\text{W}). \qquad (3)$$

C. Sample Results

The analysis of the previous section is applied to a practical example using a CO_2 laser (λ = 10.6 μm) with P_L = 1 TW. The results are shown in Fig. 2. Acceleration gradients of $\Delta W/L > 1$ GeV/m are possible at phase slippages $\Delta\phi/\pi \sim 0.1$ for axicon focusing angles $\theta \sim 10$ mrad. At these high angles a_o must be small (<0.3 mm) in order to limit L (~3 cm). Larger beam sizes (~1 mm) are possible if θ is reduced or less stringent phase slippage is acceptable.

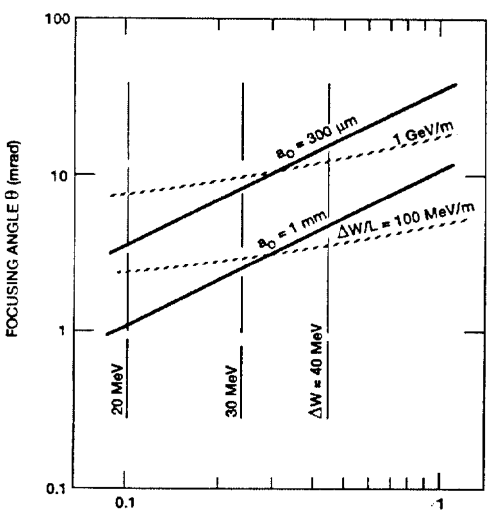

Figure 2. Parameter map for vacuum laser acceleration assuming a laser peak power $P_L = 10^{12}$ W and λ = 10.6 μm.

IV. SUMMARY

Both schemes presented here have the potential of creating high acceleration gradients (>1 GeV/m). While some realistic examples were investigated for near-resonance ICA [5], other gases and laser wavelengths should be examined. For the vacuum accelerator, issues such as optical damage caused by the small laser beam size need to be addressed. Using cylindrical optical waveguides may be a possible solution [5].

V. ACKNOWLEDGMENTS

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