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LASER FOCUSING OF PARTICLE BEAMS*

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ABSTRACT

We propose a scheme using the Inverse Cerenkov effect to focus particle beams with the potential of high focusing gradients (~ 200 kG/cm) and rapid, accurate control of the focusing element.

1. INTRODUCTION

The extremely high fields available in lasers have led various people to propose schemes to use those fields to accelerate particles. Many of these schemes continue to show great promise.

In general, particle beams must not only be accelerated longitudinally, but they must be focused in the transverse directions, sometimes to extremely small spot sizes. In this paper we propose a technique for using the high fields in lasers to do this focusing. The scheme we propose does, with fairly conservative assumptions, yield high focusing gradients in small focusing elements at modest laser power and with the potential for very fast, accurate control of focal placement and strength. With more optimistic assumptions on gas breakdown and laser power, the potential equivalent gradients approach the MG/cm level. However, even the gradients achievable with conservative assumptions (~ 200 kG/cm) are so large (and are combined with the virtue of fast accurate control) that we believe our proposed technique merits serious attention.

In the next section we describe our scheme qualitatively and discuss its potential. In Sec. III of this paper, we present a detailed analysis of the basic interaction in a 2-D planar model, starting from first principles (that is, Maxwell's equations and the Born approximation for the particle motion). This analysis illustrates the essential ingredients and provides quantitative estimates of the expected focusing strength, required gas density, and laser power. In Sec. IV the basic interaction is analyzed again in a cylindrical geometry using the paraxial ray equation. Essentially the same result as that of Sec. III is obtained. The Gaussian laser modes used in Secs. III and IV are clearly not the optimum modes; in Sec. V we build on the work done on Inverse Cerenkov Acceleration with axicon-focused laser beams to find yet

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another, more optimistic, estimate of the basic interaction. The reader can thus choose between a first-principles approach that may not be physically transparent (Sec. III), a more intuitive approach familiar to those in optics (Sec. IV), and an advanced treatment that offers the best results (Sec. V). In Sec. VI we briefly discuss the effect of gas scatter on the particle beam, and in the final section we summarize and discuss our results.

II. GENERAL DISCUSSION

The basic geometry we have in mind is shown in Fig. 1 where the laser electric field at the focal waist is primarily radial and is assumed to vanish on axis. A particle, as shown, traveling near the axis would indeed feel very strong focusing or defocusing forces from the electric field. However, the particle would also feel a force from the laser magnetic field, which would cancel the electric force to order $1/\gamma^2$, where γ is the relativistic mass factor. In this paper, we ignore all terms of order $1/\gamma^2$ as being too small to be of interest. Thus, in this approximation, the basic interaction of particle with laser focus vanishes.

Adding gas to the region of the laser focus has three principal effects. First, and most importantly, the electric and magnetic fields no longer balance to order $(\epsilon-1)$, where ϵ is the dielectric constant of the gas; this implies that the interaction of a particle with the laser focus no longer vanishes. The next effect of the gas is to introduce a difference in velocity between the particle ($v = c$) and the light ($v < c$, if $\epsilon > 1$). This effect causes a continuous phase shift and implies that the basic interaction must have finite range; that is, we cannot use plane waves.

Fig. 1. General configuration and typical dimensions (not to scale).

The final effect of the gas is to limit the peak laser field to a value below breakdown. (It is possible that a plasma at the focus might also yield focusing, but we have not analyzed this case.) Breakdown values in gas depend strongly on laser pulse length and are not well known. We will use values appropriate to a 20-ps laser pulse (~ 20 GeV/m), even though actual pulse lengths may be shorter (~ 3 ps) and breakdown values presumably higher. Breakdown limits may also depend on pressure, although fairly weakly, but this dependence is not well understood at such short pulse lengths. Clearly, more experimental work needs to be done to explore the ultimate limits of our focusing technique.

In later sections, we present detailed models and explicit estimates for the focusing strength; here we summarize the results of the analysis qualitatively. The interaction of the particle with the light depends on the imbalance of E and B and is thus proportional to $(\epsilon - 1)$. The interaction is maximized if the phase slip through the Rayleigh length (approximate length of laser focus) is a fraction ($\sim 1/3$) of π . Finally, the interaction is optimized if the angle θ , between the particle and the light [$\sin \theta \sim (\text{waist width})/(\text{Rayleigh length})$] is the Cerenkov angle θ_c . Our scheme can be described, essentially, as inverse Cerenkov focusing.

A difficulty that comes immediately to mind is that the interaction depends on the phase of the particle with respect to the light wave and can, depending on this phase, be either focusing or defocusing. There are two obvious solutions to this problem. The first is to accept the situation, that is, defocusing of half the particles. The remaining particles can be focused strongly enough to give a very high gain in luminosity. The second is to prebunch the particles at the correct phase. This might be possible, say with a free-electron laser.

A possible set of laser focus dimensions is shown in Fig. 1 (~ 0.2 mm $\times$ 6 mm) for a CO₂ laser ($\lambda \sim 10$ μ m). This is not obviously the optimum configuration and, in particular, the optimum sizes probably shrink as the laser wavelength decreases. Thus, for some applications, a glass laser or a laser with even shorter wavelengths, such as KrF, might be appropriate. In general, a complete optimization (including laser wavelength, breakdown level, pulse length, gas pressure, and laser configuration and parameters) has not been done. We will use a set of parameters that are fairly conservative, probably achievable, and yet that produce quite impressive results with very modest laser power.

III. PLANAR MODEL

In this section let us analyze a planar (that is, Cartesian) model assuming a Gaussian laser beam. We begin with Maxwell's equations and analyze the effect on particles using the Born approximation.

The geometry and coordinates are shown in Fig. 2. We assume a mode in which the laser magnetic field is purely z -directed ($B_x = B_y = 0$) and the electric field direction lies in the x, y

Fig. 2. Coordinates used in the analysis in Sec. III.

plane ($E_z = 0$). The relevant Maxwell's equations are then

$$\frac{\partial B_z}{\partial y} = \frac{\epsilon}{c} \frac{\partial E_x}{\partial t} \quad , \quad (1)$$

$$\frac{\partial B_z}{\partial x} = -\frac{\epsilon}{c} \frac{\partial E_y}{\partial t} \quad , \quad \text{and} \quad (2)$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = \frac{1}{c} \frac{\partial B_z}{\partial t} \quad , \quad (3)$$

where ϵ is the dielectric constant. From Eqs. (1)-(3) we can easily obtain the wave equation

$$\frac{\epsilon}{c^2} \frac{\partial^2 E_y}{\partial t^2} = \frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} \quad . \quad (4)$$

Writing the solution of this equation as a superposition of traveling waves we find

$$E_y = \int_0^\infty dk \, E(k) \sin ky \cos(kx - \omega t) \quad , \quad (5)$$

where

$$K \equiv \sqrt{\frac{\epsilon \omega^2}{c^2} - k^2} \quad , \quad (6)$$

and where

$$\bar{E}(k) = 0 \quad \text{if} \quad |k| > \frac{\omega}{c} \quad \epsilon \quad . \quad (7)$$

To determine $\bar{E}(k)$, we impose the initial-boundary-value condition

$$E_y(x=0, y, t=0) = \sqrt{2\epsilon} E_D \cdot \left(\frac{y}{L}\right) e^{-\left(\frac{y}{L}\right)^2} \quad , \quad (8)$$

where E_D is the peak electric field at the waist. We then find that

$$\bar{E}(k) = \frac{1}{2} \sqrt{\frac{2\epsilon}{\pi}} k L^2 E_D \exp \left[-\frac{L^2}{4} \left(\frac{\epsilon \omega^2}{c^2} - k^2 \right) \right] \quad . \quad (9)$$

The electric and magnetic fields are thus, near $y = 0$,

$$E_y = \frac{1}{2} \sqrt{\frac{2\epsilon}{\pi}} L^2 E_D y \int_0^{\frac{\omega}{c}} dk K \exp \left[-\frac{L^2}{4} \left(\frac{\epsilon \omega^2}{c^2} - k^2 \right) \right] \cos(kx - \omega t) \quad , \quad \text{and} \quad (10)$$

$$B_z = \frac{1}{2} \sqrt{\frac{2\epsilon}{\pi}} L^2 E_D y \left(\frac{\epsilon \omega}{c} \right) \int_0^{\frac{\omega}{c}} dk K \exp \left[-\frac{L^2}{4} \left(\frac{\epsilon \omega^2}{c^2} - k^2 \right) \right] \cos(kx - \omega t) \quad . \quad (11)$$

To evaluate the effect of these fields on the particles, we use the Born approximation, that is,

$$\Delta P_y = \int_{-\infty}^{\infty} dt F_y \quad , \quad (12)$$

where ΔP_y is the change in y-momentum, where $F_y = q(E_y - B_z)$ is the y-component of the force, and where we use the trajectory

$$y = \text{const} \quad , \quad \text{and} \quad (13)$$

$$x = c(t - t_0) \quad , \quad (14)$$

where t_0 is the time of arrival of the particle at $x = 0$ (assumed arbitrary). Using Eqs. (10), (11), (13), and (14) in Eq. (12), we find

$$\begin{aligned} \Delta P_y = & \frac{1}{2} \sqrt{\frac{2e}{\pi}} L^2 (qE_D)_y \left\{ \int_0^{\frac{L}{c}} \sqrt{\epsilon} dk \exp \left[-\frac{L^2}{4} \left(\frac{\epsilon \omega^2}{c^2} - k^2 \right) \right] \right. \\ & \left. \cdot \left(k - \frac{\epsilon \omega}{c} \right) \int_{-\infty}^x dt \cos (kct - \omega t - kct_0) \right\} . \end{aligned} \quad (15)$$

Using the fact that

$$\int_{-\infty}^{\infty} dt \cos \alpha t = 2\pi \delta(\alpha) \quad , \quad (16)$$

where δ is the Dirac delta function, Eq. (15) reduces to

$$\Delta P_y = -\sqrt{2\pi e} (\cos \varphi_0) (qE_D)_y \frac{L^2 \omega^2}{c^3} (\epsilon - 1)^{3/2} \exp \left[-\frac{L^2 \omega^2 (\epsilon - 1)}{4c^2} \right] , \quad (17)$$

where φ_0 is the wave phase at the time of the particle's arrival at $x = 0$. We choose the gas pressure, and thus ϵ , so as to maximize Eq. (17). We thus choose

$$\epsilon = 1 + \frac{6\lambda^2}{4\pi^2 L^2} \quad , \quad (18)$$

where λ is the wavelength of the laser. With this optimization, Eq. (17) reduces to

$$\Delta P_y = -\cos \varphi_0 \sqrt{2\pi} e \left(\frac{6}{e}\right)^{3/2} (qE_p) \frac{c}{\omega} \left(\frac{\lambda}{L}\right) . \quad (19)$$

The focal length L_F is

$$L_F = \frac{P_{xy}}{\dot{L} P_y} \quad (20)$$

and is given by

$$L_F = 2 \sqrt{\frac{e}{2e}} \left(\frac{e}{6}\right)^{3/2} \left(\frac{L}{\lambda}\right) \left(\frac{\gamma mc^2}{qE_p}\right) \left(\frac{1}{\cos \varphi_0}\right) . \quad (21)$$

Equation (21) is our basic result. Note that by decreasing L/λ , we can decrease the focal length; however, from Eq. (18) we see that the price we pay is that we must increase the pressure. The peak laser power required, P , can be estimated to be

$$P \approx \frac{(\pi L^2) E_p^2 c}{4\pi} . \quad (22)$$

As an example, let us assume

$$\begin{aligned} \gamma mc^2 &= 50 \text{ GeV} , \\ qE_p &= 20 \text{ GeV/m} , \\ L/\lambda &= 10 \text{ (} \rightarrow \text{ pressure } \sim 10 \text{ atm)} , \text{ and} \\ \varphi_0 &= 0 \text{ (maximum focus)} . \end{aligned} \quad (23)$$

We then find

$$\begin{aligned} L_F &= 11.25 \text{ m} , \text{ and} \\ P &= 10^{10} \text{ W} . \end{aligned} \quad (24)$$

For a magnet of the same length (equal to $2\pi L^2/\lambda$) to produce the same deflection, it would have to have a field gradient $qB' \sim 220 \text{ kG/cm}$, a quite high value.

Thus, with modest peak power (10^{10} W) and reasonable gas pressure (~ 10 atm), we can produce very strong focusing with a fairly conservative value of the breakdown limit. Optimistic assumptions about laser pulse lengths and gas breakdown would allow us to push the equivalent gradients into the range of 1 MG/cm, albeit at the expense of greater laser power. The ability to accurately adjust the focal position, phase, and strength on a fast time scale makes this scheme very attractive.

IV. PARAXIAL EXPRESSION FOR A SINGLE FOCAL ELEMENT

Electrons that travel at the speed of light experience no focusing force because the electric field and the induction forces exactly balance. This cancellation does not occur in a dielectric medium of refractive index n where the net force is proportional

to $(n^2 - 1) \sim 2(n - 1)$. Coincident with focusing, the electron sees a phase modulation $(n - 1)\omega t$, where $\omega = 2\pi/\lambda$, λ being the wavelength and t the time. When the electrons travel through a TEM₀₁ Gaussian beam mode, this dielectric modulation is chosen roughly to match one-third its period to a Rayleigh range Z_r .

Consider the following y component of the exact Gaussian electric-field mode, represented as an integral over the transverse components of the wave number $\underline{k}$ at location $\underline{x}$:

$$E_y = C_0 \int_{-\infty}^{\infty} dk_y dk_x i k_y \exp \left[-\frac{1}{4}(k_x^2 + k_y^2)\omega_0^2 + i \underline{k} \cdot \underline{x} - i\omega t \right] , \quad (25)$$

where we use the paraxial approximation, $k_x, k_y \ll k$, $\underline{k} = [k_x, k_y, k_z]$, $\underline{x} = [x, y, z]$, and

$$k_z = [k^2 - k_x^2 - k_y^2]^{1/2} \approx k - (k_x^2 + k_y^2)/(2k) \quad (26)$$

to compute the fields to lowest significant order. The convention we use for the field is that the right-hand side of the equation is the real part of what is written. The quadrature requires evaluation of

$$\int_{-\infty}^{\infty} dt \begin{bmatrix} 1 \\ t \end{bmatrix} \exp(-At^2 + iBt) = \begin{bmatrix} 1 \\ iB \\ 2A \end{bmatrix} \sqrt{\frac{\pi}{2A}} \exp(-B^2/4A) , \quad (27)$$

giving

$$E_y = \sqrt{2e} E_B \frac{y}{z_0} \frac{\exp \left[-\frac{x^2 + y^2}{z_0^2 (1 + iz/z_r)} + i k z - i \omega t \right]}{(1 + iz/z_r)^2} \quad (29)$$

where $z_r = k_0^2/2$, and we have renormalized the field to its peak value E_B at the focal plane $z = 0$. The x-component of the induction is given by

$$B_x = -k E_y / \omega [1 + \epsilon(k_y/k)^2] \quad (29')$$

Integration of the transverse force $q(E_y - cB_x)$ over the electron particle trajectory

$$\underline{x} = [0, y, ct + c/k] \quad (30)$$

in the spirit of the Born approximation, gives the transverse impulse. The ratio of the electron impact parameter y to the focal length is evaluated on axis by dividing the impulse by the momentum

$$\frac{y}{f} = \frac{q}{mc\gamma} \int_{-\infty}^{\infty} (E_y - cB_x) dt \quad (31)$$

Using the expressions for the fields, this gives

$$\frac{W_0}{f} = 2^{3/2} e^{1/2} \frac{(1-n) q E_B}{mc\gamma} e^{i\psi} \int_{-\infty}^{\infty} \frac{e^{i(n-1)\omega t}}{(1 + iz/z_r)^2} dt \quad (32)$$

where q is the electron charge, m its mass, and γ its total energy measured in rest mass units. Completing the contour in the lower half-plane by an infinite semicircle and using the residue of the integrand, we obtain

$$\frac{W_0}{f} = -2^{5/2} e^{1/2} \pi \frac{q E_B}{\omega mc\gamma} \delta^2 e^{-\delta} \cos \psi \quad (33)$$

where δ is a measure of the refractive index,

$$\delta = (n - 1)\omega z_r/c \quad . \quad (34)$$

Optimization with respect to δ gives

$$\frac{W_0}{F} = -2^{7/2} e^{-3/2} \frac{qE_B^2}{mc^2 \gamma} \cos \psi \quad , \quad (35)$$

which, except for a factor near 1, is the inverse of Eq. (21).

V. FOCUSING WITH SINGLE- Θ LASER BEAMS IN A GAS

A laser configuration that has been proposed for acceleration¹ consists of a continuous set of plane waves in a gas medium, all converging on the z-axis at the same angle Θ , related to the index n of the medium and the speed βc of the particles by the Cerenkov relation $n\beta \cos \Theta = 1$.

This configuration has also focusing properties, given for an electron of charge $-e$ by the radial force²

$$F_r(r, \psi) = qE_0 \tan \Theta J_1(kr \tan \Theta / \beta) (-\sin \psi) \quad , \quad (36)$$

where

$\psi = kct - nkz \cos \Theta$ is the (constant) phase angle of a particle,

E_0 = the peak field on the z-axis, and

$k = 2\pi/\lambda$ is for the vacuum wavelength.

For $r \ll \beta\lambda/\tan \Theta$, $\beta \approx 1$, and $\tan \Theta \approx \Theta$:

$$F_r(r, \psi) = [-qE_0 \epsilon^2 (\pi/\lambda) \sin \psi] r \quad . \quad (37)$$

Thus, an electron traveling in the general +z-direction at a distance r from the axis will perform betatron oscillations

$$r(z) \propto \sin(z/\beta_\perp) \quad , \quad (38)$$

where

$$\beta_\perp^2 = \frac{\gamma mc^2}{qE_0 (\pi/\lambda) \Theta^2 \sin \psi} \quad . \quad (39)$$

There is focusing in the range $0 < \psi < \pi$ and defocusing otherwise.

When the length L of the laser interaction region is small compared with β_L , there is still a focusing (or defocusing) effect that can be calculated by considering the angle α by which a particle entering the region parallel to the z -axis and with a given r is deflected away from the axis. If p_z is the axial momentum and Δp_r the acquired radial momentum over L ,

$$\alpha = \tan \theta = \frac{F_r L / \beta c}{\gamma m \beta c} = \left[\frac{-q E_0 \epsilon^2 L (\pi / \lambda) \sin \psi}{\gamma m c^2} \right] r \quad (40)$$

for $\beta \approx 1$.

The focal length of this lens is

$$f = \frac{r}{-\tan \alpha} = \frac{\gamma m c^2}{q E_0 \epsilon^2 L (\pi / \lambda) \sin \psi} \quad (41)$$

Substituting E_0 as a function of L , λ and the total power P in the laser beam,³ we obtain

$$f = 2.3 \times 10^3 \frac{\gamma \lambda^{3/2}}{\epsilon^3 L^{1/2} P^{1/2} \sin \psi} \text{ (mks units)} \quad (42)$$

For example, with $\epsilon = 52$ mrad (corresponding to hydrogen at 10 atm), $\lambda = 10^{-5}$ m, $\gamma = 10^5$ (that is, 50 GeV), $L = 10^{-2}$ m, and $P = 10^{10}$ W, we have

$$f = 5.3 / \sin \psi \quad (43)$$

which is about a factor of 2 better than the result [Eq. (24)] obtained for a Gaussian laser beam.

VI. GAS SCATTER

A beam propagating through a gas will show an increase in emittance caused by molecular collisions. B. W. Montague has given a method⁴ to calculate this increase in the presence of a focusing force. For a given betatron focusing function β_L , the normalized (that is, invariant) emittance growth is⁵

$$\Delta \epsilon = \frac{2F}{\gamma^2} [\gamma_f^{1/2} - \gamma_i^{1/2}] \quad ,$$

where γ' is the rate of increase in γ , and the subscripts f and i indicate the final and initial values. The function F is given as⁶

$$F = 2\pi r_e^2 N \ln \left(\frac{\epsilon_{\max}}{\epsilon_{\min}} \right) \frac{\beta_{\perp}}{\gamma^{1/2}} ,$$

where $r_e = 2.8 \times 10^{-15}$ m is the classical electron radius, and $\epsilon_{\max}$ and $\epsilon_{\min}$ are the extreme atom collision deflection angles for the particles.

We now use these expressions to calculate $\Delta\epsilon$ for the short-lens case discussed above, taking $\psi = \pi/2$ for no acceleration and maximum focusing. With $\ln(\epsilon_{\max}/\epsilon_{\min}) = 10$ and using $\beta_{\perp} = 4 f/2\pi$, we have

$$\Delta\epsilon = 8.5 \times 10^{-3} \left[\frac{fLp}{\gamma} \right] ,$$

where the emittance, focal length, and interaction length are in meters, and p is the gas pressure in atmospheres.

For the example above, with $f = 5.3$ m, $L = 10^{-2}$ m, $\epsilon\gamma = 10^5$, and $p = 10$ atm we obtain

$$\Delta\epsilon = 4.2 \times 10^{-8} \text{ mrad} .$$

The focusing (positive or negative) properties discussed above apply to particles with a given phase ψ relative to the laser fields; because of the Cerenkov condition this phase is conserved during the interaction when a sufficiently large β is assumed. For beams unbunched at the laser wavelength, a continuous variation in ψ occurs along the beam, resulting in all the possible positive and negative values of the focal length f given by Eq. (7). Nevertheless, a positive focusing effect can be obtained for all ψ 's by using a succession of lenses phased so the ψ of any particle increases by $\pi/2$ between lenses. Four such lenses provide overall positive focusing for any particle in the beam.

VII. DISCUSSION

We have presented analyses of simple models starting from either Maxwell's equations or the paraxial ray equation, which show that with reasonable assumptions on laser power, gas breakdown, and gas pressure we obtain very high focusing forces. Using more sophisticated models developed for inverse Cerenkov accelerators, we have seen that we can do even better. Optimistic scaling of breakdown with laser pulse length would imply that even higher focusing forces (~ 1 MG/cm) might be available.

Our scheme has a number of obvious advantages that merit attention. With conservative assumptions on breakdown, we obtain

very high focusing fields: with the potential (with favorable breakdown scaling) of extremely high focusing forces. Perhaps more intriguing is the possibility that such strong focusing can be very rapidly and accurately controlled by optical techniques. This fast and accurate control is partially because our scheme requires very little solid material near of the particle beam; the focusing element is the laser focus and requires only gas to be effective. Finally, the laser power required is modest and thus readily available, although high repetition rates at short pulse lengths may still require some development.

Essentially, what we have done is to turn the Inverse Cerenkov Acceleration scheme into a focusing scheme. It is probable that other laser acceleration schemes, for example droplet or beat-wave schemes, can also be used for focusing. Our scheme has the advantage of simplicity; namely, the medium (gas) is passive and is not required to have any coherent structure, with the result that fast accurate control depends primarily on the optical elements. On the other hand, it is likely that other schemes, in particular the beat-wave scheme, may give even higher focusing forces than our scheme. The droplet scheme is intermediate between the two schemes in that it may provide easy control, if the droplet formation can be done accurately, and yet have higher focusing forces than our scheme. Thus, our scheme has the relative advantage of simplicity, but it is clear that all the techniques should be investigated for their focusing potential.

A number of topics still need investigation. The limits of our scheme depend on gas breakdown at short pulse lengths and can probably be best studied experimentally, although adequate focusing seems to be available even with conservative breakdown assumptions. Clearly the most important task is to create an optimized design for some particular purpose, such as, for example, final focusing in the Stanford Linear Collider. The examples we have presented have not been optimized in any sense. Finally, it would be useful to have a detailed design, including laser "architecture," to see how such a system might actually fit into accelerator systems and to determine whether any relevant technologies require further development. The potential great advantages of laser focusing would certainly seem to justify such studies.

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