LASER ACCELERATOR FOR ULTRA-HIGH ENERGIES

T. Tajima
Department of Physics and Institute for Fusion Studies
University of Texas, Austin, Texas 78712

Abstract

It is shown that under appropriate conditions the laser electromagnetic wave is trapped in a plasma fiber and is capable of exciting a beat plasma wave with a flat phase front propagating with the speed of light c (or any desired speed). In an important special case where the fiber contains vacuum inside it is still possible to have a wave whose phase velocity is up to c in the direction of the particle propagation with a plasma slow wave structure or in curved geometry. While the parallel component of the laser field is used for acceleration, the perpendicular component is either cancelled by the imposed static magnetic field force or used directly to contain particles. In the latter way it does not seem impossible to reach multi-peta electronvolts ($> 10^{15}$eV) for protons. As examples of applications, I propose (i) direct method of collective excitations of quark-gluon systems; (ii) microscope for quark-gluon systems; (iii) method of direct interaction with spin or chiral structure of matter; and (iv) possible lasing by quark excitation.

I. Introduction

The laser beat-wave accelerator scheme[1] is capable of creating a coherent large longitudinal electric field $E_L = mc\omega_p/e$ of the order of 1 GeV/cm. Applying this scheme to an ultra-high energy accelerator has been considered.[2,3,4] Two of the difficulties associated with the original scheme identified are: (i) the longitudinal phase mismatch between the plasma wave and the particles; (ii) the tendency of laser light to spread in the transverse direction. It is crucial to overcome these difficulties in order to scale the scheme to ultra-high energies. The plasma wave excited by the beat of two laser lights has the phase velocity that is equal to the group velocity of the electromagnetic waves in the plasma[1]:

$$v_p \equiv \frac{\omega_p}{k_p} = \frac{\omega_0-\omega_1}{k_0-k_1} \cong v_{gr}^{EM} = c\left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{1/2} , \qquad (1)$$

where ω_p, ω_0, ω_1 are the frequencies of plasma wave, the first and second laser lights and $k_p = k_0-k_1$, k_0, k_1 are the wavenumbers of the plasma wave and the two laser lights. Since the phase velocity of the plasma wave is less than the speed of light, the plasma wave will be outrun by high energy particles in matter of the dephasing time $\tau_d = 2\pi(\omega_0/\omega_p)^2 \omega_p^{-1}$. The particles that are trapped by the plasma wave gain energy by $2(\omega_0/\omega_p)^2 mc^2$, calculated by using the wave breaking limit electric field $E_L = mc\omega_p/e$.

We shall show that the plasma fiber under appropriate conditions possesses a property to overcome this difficulty. The duct structure, in which the plasma density is low inside and the density is so high outside that the electromagnetic wave is evanescent, enables it to sustain a beat wave phase velocity equal to any prescribed velocity including the speed of light. In addition to this benefit the plasma fiber confines the light, overcoming the natural tendency of the transverse spreading. Thus the idea of the plasma fiber plays a central role in improving the laser beat-wave accelerator in two of the most important points. In this paper we present a set of accelerator ideas that may be collectively called plasma fiber accelerator as an outgrowth of the plasma beat-wave accelerator. We discuss these in Sec. II.

One important case of the plasma fiber accelerator is a circular or race-track accelerator for protons utilizing the laser electric field to bend their orbit in order to contain particles within a manageable size. If such a scheme proves feasible, proton energies of multi-petaelectronvolts are not out of scope. We touch upon this in Sec. III.

In the last Section applications of such an accelerator, if is is ever successfully built, are suggested. A novel aspect in these is to directly couple the macroscopic beam structure with collective modes of the microscopic subnuclear structure.

II. Plasma Fiber Accelerator[6]

A way to match the phase of the accelerating field with high energy particles is to inject particles oblique to the electric field direction [see Fig. 1(a)]. In order to phase-lock, the angle θ between the particle momentum and the electric field is given by

$$\cos\theta = \left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{1/2} . \qquad (2)$$

Although we match the parallel phase, we have now introduced an extraneous perpendicular acceleration, which bends the particle orbit (perhaps undesirably). To correct this situation, it was proposed[5] that a static vertical magnetic field is imposed. The magnetic field is such that

$$\frac{B}{E} = \sin\theta = \frac{\omega_p}{\omega_0} , \qquad (3)$$

for relativistic particles where B is out of the board in Fig. 1(c).

An alternative approach is to conduct the laser lights in a plasma duct where the plasma density in the middle is low and the edge density high [see Fig. 1(b)]. We choose the outside density so high that the electromagnetic waves are evanescent there and therefore they are trapped within the duct structure (plasma fiber). By choosing a right width of the duct we can show that the beat wave velocity matches the speed of light. Let us choose flat densities n inside the duct and n' outside of it with the duct width d. We demand the frequency matching among the two lasers and the plasma wave:

$$\omega_0-\omega_1 = \omega_p . \qquad (4)$$

Further, we demand the parallel velocity of the two lasers which is equal to the parallel phase velocity of the plasma wave be the speed of light:(*)

$$v_{gr\parallel}^{EM} \equiv \frac{\omega_0-\omega_1}{k_{\parallel 0}-k_{\parallel 1}} = v_{ph\parallel} = c , \qquad (5)$$

where

$$k_{\parallel j} = \left[\frac{\omega_j^2}{c^2} - \frac{\omega_p^2(r)}{c^2} - \left(\frac{2\pi}{d}\right)^2\left(n_j + \frac{1}{2}\right)^2\right]^{1/2} \qquad (6)$$

and j=0 or 1 and we choose $n_0 = n_1 + 1$, where n_j are the number of transverse nodes. From Eqs. (4)-(6), we obtain

$$d = \sqrt{2n_1}\left(\frac{\omega_0}{\omega_p}\right)^{1/2}\left(\frac{2\pi c}{\omega_p}\right) . \qquad (7)$$

The density n' at the evanescent region should be

$$n' > n + \frac{9\pi mc^2}{4e^2d^2} . \qquad (8)$$

The plasma wave phase front is straight, i.e.

$\phi(z,r) \sim A(r)\cos(k_{\parallel p}z-\omega_p t)$ [see Fig. 1(b)]. Table 1 presents a tentative list of parameters for a typical 200 TeV collider using the present scheme.

The above-mentioned role of the plasma fiber leads to a generalization of the plasma fiber accelerator. The original beat-wave accelerator was invented to create a slow wave out of the fast electromagnetic waves in a plasma via the nonlinear beat-wave coupling. It is, however, possible to impose a slow wave structure in a more "traditional way" employing the ripple structure (irises) on the fiber surface[2] (see Fig. 2). The index of refraction of the plasma may be given as

$$n^2(r,z) = 1 - \omega_p^2(r,z)/\omega[\omega \pm \omega_{ce}(r,z)] , \quad (9)$$

where $\omega_{ce} = eB_z/mc$ and the z-dependence refers to the ripple structure. To state in a simplistic way, the duct structure makes the laser electric field possess the parallel component, while the ripple structure makes the electromagnetic wave be a slow wave. If the relation

$$\frac{\omega}{k+\Delta k} = c \quad (10)$$

is satisfied, the slow wave is in phase with high energy particles, where Δk is the ripple wavenumber.[6] Then the particles may be accelerated resonantly. The electric field component perpendicular to the particle propagation can be cancelled by imposed magnetic field as discussed through Eq. (3). In this variation of the plasma fiber accelerator it utilizes the laser electric field directly as an accelerating field and, therefore, it is not necessary to have a plasma inside of the plasma fiber as a special case. In this last scheme we no longer rely on the beat wave.

III. Pevatron

To further extend the last idea, it is possible to directly utilize the perpendicular laser electric field uncancelled by the magnetic field for bending the particle (proton) orbit. A typical perpendicular electric field of CO_2 lasers can amount to a 10M gauss equivalent magnetic field. It is of great interest if one can use this laser electric field to contain particles. However, if the particle is moving with c in the direction of the electromagnetic wave whose phase velocity is also c , the electric force is exactly cancelled by the magnetic force. In the plasma fiber (without irises), however, the electromagnetic wave is a fast wave: $v_{ph}/c = \frac{1}{n} > 1$. Thus there leaves a net acceleration which acts as a centripetal force for the circular motion created by the unbalanced electric field:

$$\underset{\sim}{E} + \frac{\underset{\sim}{v}}{c} \times \underset{\sim}{B} = -\hat{r}E_0\left(1 - \frac{v}{c}\, n\right) \cong -\hat{r}E_0(1-n) , \quad (11)$$

which points toward the center of the circular motion. In curved geometry (or cylindrical geometry in particular) there exists a radius (the marginal radius) at which the tangential velocity of the wave phase front is equal to c. Since the electromagnetic wave in the plasma fiber is a fast wave of TE_{111}-like mode, this radius is smaller than the radius of the fiber center.[7] If we inject high energy particles in the azimuthal direction at the marginal radius at a right phase with the electromagnetic wave, we can contain the particles with the perpendicular electric field of the laser and at the same time accelerate them with the parallel field. Such a proton accelerator may take a circular shape or a race-track shape. The laser lights are confined and conducted in and along the curved plasma fiber. In the case of the race-track the main parallel acceleration can take place in the straight sections. In either case the laser is injected at an interval of the pump depletion. It does not seem impossible to have a 10km system at 1PeV. The plasma shaping may be accomplished by regulated gas puffing, plasma injection guided by a weak vertical magnetic field, axial magnetic field stronger toward the center of the fiber, etc. (There might be a regime in which some metal wall withstands a very short high frequency laser field.)

IV. Direct Method of Collective Excitation of Quark-Gluon Systems

If a hadron collider characterized by Table 1 is ever successfully built (or its lepton collider counterpart with less luminosity because of beamstrahlung problems), its potential applications can be novel one in addition to the traditional colliding events experiments. In the following we present several ideas whose central theme is a direct coupling of the macroscopic beam structure with collective modes of the strong interaction (the quark-gluon subnuclear system where the coupling constant $g^2/\hbar c \sim 1$).

To be concrete, let us hve two colliding beams of proton and (anti-) proton or proton and electron. It is important to notice that for the incoming proton beam (beam 1) with the relativistic factor $\gamma_1 = 10^5$ (i.e. in the frame of the incoming proton beam) the structural length ℓ of the counter-streaming proton or electron beam (beam 2) is Lorentz-contracted by the γ_1 factor:

$$\ell' = \frac{1}{\gamma_1}\,\ell , \quad (12)$$

where ℓ' is the structural length in the incoming proton beam frame. If the structural length ℓ such as the length of density modulation of beam 2 is 10^{-8}cm(=1Å), the structural length ℓ' in the frame of the incoming proton beam 1 is 10^{-13}cm(=1 fermi) and the period of modulation is $\ell'/c \approx 10^{-23}$sec. Thus it is possible to collectively excite the strongly interactive subnuclear system by the modulated beam. The structural length ℓ of 1Å can be obtained by the Raman backscattering of an electromagnetic wave or the wiggler magnetic fields through the free electron laser mechanism. When the counterstream beam 2 is protons ($\gamma_2 = 10^5$), we shine CO_2 laser light (wavelength 10μ) against the counterstreaming proton beam, while when the beam 2 is electrons ($\gamma_2 = 10^8$), we impose wiggler fields with periodicity of 1 cm. Because the Lorentz contraction of the original electromagnetic (or magnetic) wavelength λ, the wavelength of the density modulation λ' becomes in the frame of beam 2 as

$$\ell = \lambda' = \frac{1}{2\gamma_2}\,\lambda . \quad (13)$$

The wavelength should be ~1 cm for electron beams of $\gamma_2 = 10^8$ and ~10μ for proton beams of $\gamma_2 = 10^5$. In either case the beam density should be in the neighborhood of solid density, which is achieved in the parameters of Table 1.

The collective motion of the quark-gluon system such as the quark-gluon plasmons and phonons may be mapped out by the ensuing part of the counterstreaming beam 2. Just like in the conventional electron microscope, one could arrange appropriate magnetic lenses to make images. In addition to the longitudinal density modulation of the counterstreaming beam, it may be possible to modulate either the transverse momentum, angular momentum, or spin with the same structural length $\ell = 10^{-8}$ cm. Then we speculate that such a structure couples collectively with the spin or chiral structure of the subnuclear matter.

Lastly, once we excite collective modes of the quark-gluon system, it might be possible to make lasing so that the radiation from one of the subnuclear matter induces the others. This would give rise to a "laser" of wavelength 10^{-13} cm.

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(*). To be precise, this speed c should be the particle velocity.

Table 1

An example of 200 TeV proton collider parameters

scheme	plasma fiber accelerator
laser	CO_2 laser
plasma density	$n_p = 10^{16}/cm^3$
machine length	$L = 10$ km
accelerating field	$E_\parallel \sim 0.1$ GeV/cm
relativistic factor	$\gamma = 10^5$
number of particles per bunch	$N = 10^7$
bunch length	$\ell_b = 10\mu$
pulse length	100 ps
pulse per sec	10^{-7}
energy per particle	$\gamma mc^2 = 10^{-5}$ J
radius of beam	$r = 10\mu$
beam radius at focus	$a = 10^{-7}$ cm
f-number	$F = 100$
momentum spread of beam	$\Delta p/p \sim 10^{-6}$
luminosity	($\mathscr{L} = 10^{33}$ sec^{-1} cm^{-2})
total power	($W = 10^7$ watt)

Figure Captions

Fig. 1: Matching the plasma wave phase with the particle. (a) tilting the plasma wave direction. (b) plasma fiber. (c) cancellation of the perpendicular acceleration by magnetic field.

Fig. 2: Slow wave structure on the plasma fiber. n_j refers to the plasma index of refraction.

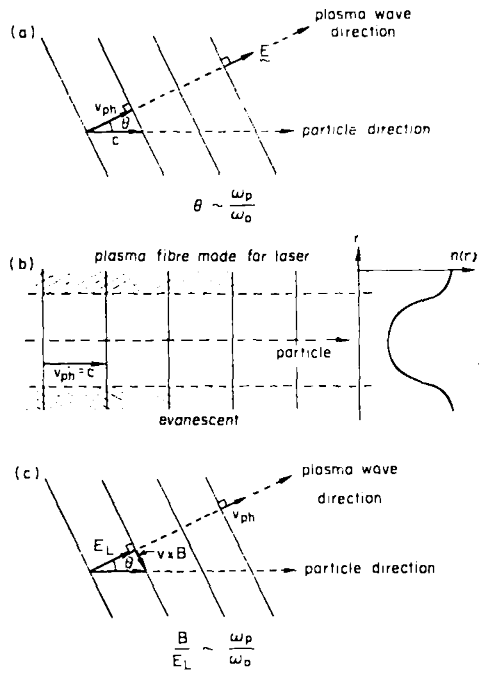

FIG. 1

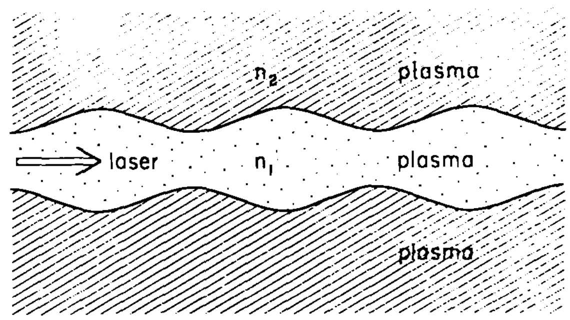

FIG. 2