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Ionospheric Accelerator

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Abstract

Ionospheric acceleration of high energy particles by a short wavelength microwave pulse is discussed. The intense electromagnetic waves in an ionospheric ($F2$) or magnetospheric plasma can be self-trapped above a threshold power. The self-binding property and the consequent self-induced transparency of the triple soliton structure of two electromagnetic waves and a plasma wave allow the propagation of an intense electromagnetic pulse without the severe and wasteful distortion that accompanies low power pulse propagation. The effects of magnetospheric fluctuations on the particle beam transport are considered. The fluctuation-induced transport seems to be within the margin of tolerance for useful beam transport. Orbits of negatively charged particles are stable. While synchrotron radiation loss for electrons is prohibitive, that of muons and antiprotons is negligible. A corresponding terrestrial application is also suggested.

I. Introduction

Quest for ever higher energies in high energy physics via accelerators means that the accelerator dimension has to become ever larger or the acceleration field strength has to become ever larger, or both. Stronger accelerating electric fields generally point to shorter wavelengths of the accelerating fields because technologically (and to a good extent, physically) the power intensity of the available driver is approximately inversely proportional to the square of the wavelength. On the other hand, while the microwave and millimeter wave technologies are well developed and relatively inexpensive, the technologies of shorter wavelengths are usually much costlier and less well developed, although recent progress in laser and related technologies have made (impressive) increases in the available power. An ultimate approach in this direction of going to a short wavelength is to use X-rays for the driver.[1]

Alternatively, if we are content with the existing technologies of microwave and millimeter waves, the system size must become so large that soon we cannot hold such a machine within a decent geographical boundary. An accelerator laboratory of an ultimate dimension should be the earth's ionosphere and magnetosphere.[2] (Fermi reportedly thought about a 'world accelerator' years ago.) Nishikawa[3] further pointed out that unlike a conventional linear accelerator which is constrained by Earnshaw's law, an accelerating field in a plasma with $\nabla \cdot E \neq 0$ may be able to simultaneously achieve the longitudinal phase stability and the transverse focussing.

The advent of the plasma beatwave accelerator[4] is in line with the above observation. It has been shown[5–7] that an electromagnetic beam with enough intensity in a plasma can overcome the Rayleigh diffraction which is natural in vacuum. Rayleigh diffraction sets a restrictive limit on the focussed acceleration length on the electromagnetic wave. This self-focussing property of the plasma-radiation interaction overcomes the diffraction limit and constitutes one of the ingredients of the plasma fiber accelerator.[8] The beatwave accelerator or that version of the plasma fiber accelerator are, however, plagued by the pump depletion problem, which leads to the energetically wasteful driving of a long train of plasma accelerating fields which eventually forms a turbulent plasma in the wake.[9] (In principle, however, the linac version of the plasma fiber accelerator does not suffer from this problem. In fact this was the starting point for the work.[1])

Introduction of the wakeless triple soliton accelerator concept[10] cures the problem of the pump depletion. An appropriately shaped electromagnetic pulse interacts with another appropriately shaped pulse and can induce the accelerating plasma wave in the first half phase of interaction and the energy of the plasma wave is reabsorbed back to the pump wave in the last half phase of interaction.[10] Two electromagnetic waves and a plasma wave constitute a stable construct called the triple soliton.[11] The reabsorption property and stability of this structure is remarkable. This is a manifestation of the self-induced transparency[12] and the self-binding stability.

Using the self-focussing property to control the optical beam spreading and the self-binding stability to maintain the beam pulse, we may be able to send the optical beam over a relatively longer distance than we otherwise could. In space these features are important because it is bound to be expensive or impractical to have many orbital stations to control the beam.

A possible configuration of the ionospheric plasma accelerator is depicted in Fig. 1. In the present paper we discuss the basic feature of this concept and examine some of the crucial physics issues. We only illustrate the main idea and do not attempt to cover a wide range of problems. Electromagnetic beams as well as the particle beams surround the earth reflected by a sufficient number of orbiting space stations containing mirrors, amplifiers, power supplies, and magnets for particle beam control. Particles are accelerated between these stations and phase adjustment, as well as bending, is done at the stations.

Depending on the specific operational conditions, the height of this machine from the ground, and thus the neutral particle density and electron density, the number of stations and thus the length of each leg of acceleration and the power of each station, the possible need to predischarge the gas, injection of preaccelerated particles, etc. all vary. Also the ionospheric molecular constituents and choice of the wavelengths of electromagnetic waves are closely related. If the chosen frequency of the optical beam resonates with that of a certain molecular or atomic excitation, the beam may be strongly absorbed and the path becomes opaque. As the beam intensity goes up, the cross-section of ionization should go up, even if the frequency is not in resonance. A multiphoton process should also occur. Under a certain condition the following situation might be possible. After injecting a prepulse which excites an appropriate molecular or atomic excitation, we inject the main pulse that induce the stimulated radiation which we want to use for acceleration. An idea similar to this has been discussed by Hofstadter.[13] All these are important questions but are outside the scope of this paper. This paper does not present an optimal case nor exhaustively consider all the deleterious effects.

II. Ionospheric Accelerator

The stable vector soliton structure and its apparent efficacy to create the accelerating longitudinal electric field as discussed in the previous section may provide the possibility of accelerating particles with a minimal amount of external control. This observation suggests that we consider the possibility of a plasma accelerator using the plasma of the magnetosphere. The magnetosphere gas particle density varies from 10^{10} cm^{-3} at the altitude of ~ 200 km (the magnetospheric $F2$ layer) to 10^6 cm^{-3} at 800 km[14]. The electron density varies from 10^5 cm^{-3} to 10^6 cm^{-3} at the respective heights at daytime. The electron density at nighttime is much lower than this. An approximate formula for the electron density is given by the Chapman distribution[14]

$$n_e(h) = n_m \exp\left[\frac{1}{2}(1 - z - e^{-z})\right], \tag{1}$$

where $z = (h - h_m)/H$ and $H = T_e/Mg$ with $h_m = 300$ km, $n_m = 10^5 - 10^6$ cm^{-3}, and $H = 100$ km. At much higher altitude the electron density is roughly known to be

$$n_e(r) = N_0(a/r)^3 = 10^4 L^{-3}\ , \tag{2}$$

where $L = r/a$ and $1.2 < L < 3 - 4$. Although the plasma density is rather low in space in comparison with the laboratory plasma, a definite advantage is its tremendous size. The electron density can increase if the power of electromagnetic waves are high enough and its frequency is close to molecular resonance because of ionization.

Since in space the electromagnetic waves are controlled with much less points, the electromagnetic beams have to hold their coherent structure and intensity much longer than we could afford in the laboratory. The natural tendency of electromagnetic beams to spread, the Rayleigh diffraction, has to be arrested. We suggest that this be done by the self-focussing effect of intense electromagnetic radiation in a plasma as we discussed earlier.[5,6] In order to avoid various plasma instabilities we put the pulse length of the electromagnetic waves short enough that only electrons respond

$$t_{\text{pulse}} < (10\mu/Z_{\text{eff}})^{1/2}/\omega_{pi}, \tag{3}$$

where μ is the ratio of the average mass of the medium plasma to the hydrogen atomic mass, Z_{eff} is the effective change of the ions and ω_{pi} is the hydrogenic ion plasma frequency. With the electromagnetic radiation power P exceeding the critical power[6]

$$P_{cr} = \frac{c}{4}(mc^2/e)^2(\omega/\omega_p)^2 = 10^{10}(\omega/\omega_p)^2 \text{ watts}, \tag{4}$$

the radiation self-focusses due to its pondermotive force. This is quite a general formula independent of the radius of the electromagnetic beam. At $P = P_{cr}$ the self-focussing pondermotive effect and the natural tendency of the radiation to diverge due to Rayleigh diffraction are in a stable balance and the beam propagates at the equilibrium beam radius. With the power just above P_{cr} this radius is close to the radius at which the total electron evacuation happens[6]

$$a = a_{cr} = a_v = 2^{1/2}(c/\omega_p)I^{1/2}/(1+I)^{1/4}, \tag{5}$$

where $I = (eE/m\omega c)^2$. When $P > P_{cr}$ the electromagnetic beam self-focusses until the electron density becomes nearly zero at the axis of the beam.[6] The beam then defocusses again by the Rayleigh diffraction. The beam will repeat the self-focussing and Rayleigh diffraction giving rise to a sausage-type envelope of propagation. Here we take the electron density to be enhanced over the ambient electron density due to preionization of the beam channel. The length ℓ of acceleration to reach energy W in the magnetosphere can be estimated as

$$W = eE\ell < m\omega_p c\ell, \tag{6}$$

where the electric field E is limited by the Tajima-Dawson wave-breaking limit.[4] For $W = 10TeV$ in a plasma of density $n_e = 10^{10}$ cm^{-3} corresponding to a singly ionized plasma at height 250 km with $\omega_0/\omega_p = 100$ the length of acceleration ℓ is 1000 km or so. In this example the wavelength of the driving electromagnetic waves is about 0.3 cm. The necessary power is 10^{14} watts at the peak power. The numbers scale accordingly when the altitude of acceleration or other conditions change. A typical arrangement of microwave generators and beam benders is depicted in Fig. 1.

III. Magnetospheric Fluctuations

The earth's magnetic field at the equator is $B_e = 0.31$ gauss and decreases with L according to the dipole field $B = B_e/L^3$. In addition, the magnetic field in the magnetosphere fluctuates due to the solar wind and the perturbation from the sheet current in the geomagnetic tail.

The solar wind velocity near the earth is $3 - 8 \times 10^7$ cm/sec and its average particle density is 1-10 cm^{-3} with temperature of 10 eV. The accompanying magnetic field strength is $1 - 5 \times 10^{-5}$ gauss. Such flows and magnetic fluctuations are fairly small compared with the accelerating field strength we are discussing. Thus these low frequency magnetic fluctuations do not affect the principal process of acceleration. The fluctuations may have, however, more subtle effects on quantities such as the particle beam emittance. The beam particles suffer diffusion due to the fluctuating magnetic field. The diffusion of a beam particle in the fluctuating magnetic fields δB is calculated to be

$$D = \left\langle \delta x^2 \right\rangle / \tau_{\rm col} = e^2 \left\langle \delta B^2 \delta \ell^4 \right\rangle / \tau_{\rm col} \gamma^2 m^2 c^4, \tag{7}$$

where $\tau_{\rm col}$ is the (effective) collision time and we take $\delta x = \delta p \delta \ell / \gamma mc$, $\delta p = e \delta B \delta \ell / c$ and $\delta \ell$ is the correlation length of the magnetic fluctuations. The diffusion width over the time of flight t_f is

$$\Delta r = (D t_f)^{1/2} = (t_f / \tau_{\rm col})^{1/2} (e / \gamma mc^2) \left(\left\langle \delta B^2 \delta \ell^4 \right\rangle \right)^{1/2}. \tag{8}$$

If the length of acceleration between two stations is of the order of 10^4 km, the magnetic fluctuations that would appear to affect in the severest way the proposed ionospheric accelerator may be the pulsation of $pc4$ type.[15–18] This has a maximum magnetic amplitude of $\delta B = 10\gamma = 10$ n tesla with pulsation period of 100 sec. The Alfven velocity in the ionosphere of height 200 km-600 km is 200 km/s. The wavelength is typically 10^4 km, which corresponds to the length of acceleration – the reason why we pick $pc4$ as the most dangerous fluctuations. Let us make a rather pessimistic estimate. Take $\delta \ell = 10^4$ km, $\delta B = 10^{-5}$ gauss, $\gamma mc^2 = 30$ TeV. Then we obtain the beam scattering width in 10^4 km acceleration length is about 2 cm according to Eq.(6). If the station separation is $\sim 10^3$ km and we take $pc2$ and 3, the wavelength is $\sim 10^3$ km, the pulsation period 10 sec., $\delta B \sim 10^{-6}$ G, $\gamma mc^2 = 30$ TeV, the scattering width is 3×10^{-4} times much smaller than the value given by $pc4$. In addition to these regular pulsation some irregular pulsations appear in the relevant frequency range, which are called $pi2$ and $pi1$[17]. The radius of the self-focussed electromagnetic radiation is approximately $c/\omega_p = 5$ cm. Thus the particle beam scattering in the ionosphere appears to be tolerable. We observe that it is a big advantage to make each accelerating length shorter than the $pc4$ pulsation wavelength. It is also of interest to note that the diffusion radius in Eq.(8) is insensitive to the mass of the accelerated particles for a given energy γmc^2. Only dependence of mass is through $\tau_{\rm col}$ in Eq.(8).

The transport of optical beams is also affected by the density nonuniformity and fluctuations in the ionosphere/magnetosphere. The dielectric constant under consideration may be given by a model form of

$$\epsilon(\mathrm{x},\omega) = 1 - \frac{\omega_p^2(\mathrm{x})}{\omega^2} + \sum_{m,n} \frac{|A_{m,n}(\mathrm{x})|^2}{\omega_{mn}^2 - \omega^2}. \tag{9}$$

The electromagnetic wave propagation is determined by

$$\left(\frac{kc}{\omega}\right)^2 = [n(\mathrm{x},\omega)]^2 = \epsilon(\mathrm{x},\omega), \tag{10}$$

where the index of refraction $\epsilon(\mathrm{x},\omega)$ may be above as well as below unity. The second term on the right-hand side of Eq.(9) is due to the plasma effect, while the third term is due to the molecular and atomic effects with m, n being various resonances. The plasma frequency ω_p^2 is a function of the electron density, $|A_{m,n}|^2$ is proportional to the oscillator strength and the atomic density and, therefore, they are a function of primarily the altitude. The fluctuating parts of the densities can be in any direction. This [Eq.(9)] means that an optical beam could be deflected away from or toward the earth, depending on whether the plasma contribution to the dielectric function or the molecular contribution is dominant. This leaves a possibility that a choice of an appropriate amount of ionization and/or an appropriate value of the frequency separation from the dominant resonance $\Delta\omega = \omega - \omega_{mn}$ may make the optical orbit a straight or a geodesic path, by design.

Fluctuations of the densities can diffuse the optical beam through scattering.[9,19] The wave equation takes a form of

$$[\nabla^2 + k_0^2(1+\delta\epsilon)]E = 0, \tag{11}$$

where $\delta\epsilon$ is due to the (normalized) fluctuating density and $k_0^2 = (\omega^2 - \omega_{po}^2)/c^2$. When we write the average of the scattered wave by $\langle E \rangle$

$$\langle E \rangle = E_0 e^{i\mathbf{k}_0\cdot\mathbf{r} - \alpha x}, \tag{12}$$

the decorrelation is expressed by

$$\alpha \cong \ell_c k_0^2 \sigma^2, \qquad \text{for } \ell_c k_0 \sigma < 1, \tag{13}$$

where $\langle \delta\epsilon(\mathrm{x})\delta\epsilon(\mathrm{x}')\rangle = \sigma^2 C(\mathrm{x}-\mathrm{x}')$ with C being the autocorrelation function falling down from unity to zero on the scale ℓ_c[9,19]. The spectrum of σ and ℓ_c needs further study. For $k_0\ell_c \gg 1$, the optical beam follows the WKB ray trajectories.

IV. Discussion

There remain many critical questions unanswered. One of the important questions is that of the luminosity issue, as the ultrahigh energy accelerator has to satisfy a very stringent condition.[1,19] Another issue is the power and how we supply the necessary power. The necessary peak power $10^{10}(\omega/\omega_p)^2$ watts is compared with a typical substorm power $P \cong v_{sw}B_{sw}^2\ell_0^2 \sin^4\left(\frac{\theta}{2}\right) \sim 10^{11} - 10^{13}$ watts.[20] The method of preinjection has to be considered, too. Among many problems let us consider briefly the problem of synchrotron radiation. A schematic optical beam is shown in Fig. 2. Since the electromagnetic pulses put out electrons, the interior of each pulse will be positively charged up. Since a typical radial electron expulsion takes place over c/ω_p [see Eq.(5)], the size of the radial electric field is as large as the longitudinal one (the Tajima-Dawson value). This means that the radial field acts as a very strong focussing and defocussing force for negative charge and positive one, respectively. Positive ions have a hard time being stably trapped in the optical pulse, while negatively charged particles (such as electrons) are strongly trapped. When the optical beam is refracted by the density nonuniformity, for example, negatively charged particles may stay trapped along the optical beam orbit. However, if we choose electrons, the synchrotron radiation loss is too large. The energy loss per turn is

$$U_0(\mathrm{MeV/turn}) = 0.0885[W(\mathrm{GeV})]^4/\rho(m), \tag{14}$$

or in terms of power[21]

$$P = \frac{2r_e c\gamma^4 mc^2}{3\rho^2}Q, \tag{15}$$

where r_e is the classical electron radius and Q is the quantum correction if present, i.e. $Q \cong (W/W_c)^{4/3}$ for $W > W_c \equiv \frac{3}{2}\hbar c\gamma^3/\rho$. At $W = 100$ TeV even with the bending over 6000 km, we have $U_0 \sim 1.5 \times 10^6$ TeV/turn for electrons. If we have to bend electrons at each station over a much smaller radius, the energy loss correspondingly becomes more severe. Although we regard it important to develop this idea, we have found that the necessary parameters are too demanding for the present day technology and some physics issues remain unresolved. We speculate, however, that the process we discussed in the present paper may take place in the pulsar magnetosphere.[22]

In terms of synchrotron radiation loss perhaps negative muon may be an alternative candidate for acceleration. The utilization and more control of bending of the electromagnetic pulse according to Eq.(9) and the trapping of negatively charged particles in the pulse may make it possible to have a circular accelerator for muons and antiprotons for the terrestrial laboratory.

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Figure Captions

1. The conceptual picture of the ionosphere accelerator. The earth, its magnetosphere, and the ionosphere. The high energy particle beam and electromagnetic beams are circling around with the multiple stations in space maintaining these beam power and quality.

2. Schematic picture of the optical beam, plasma wave, charge separation, etc.

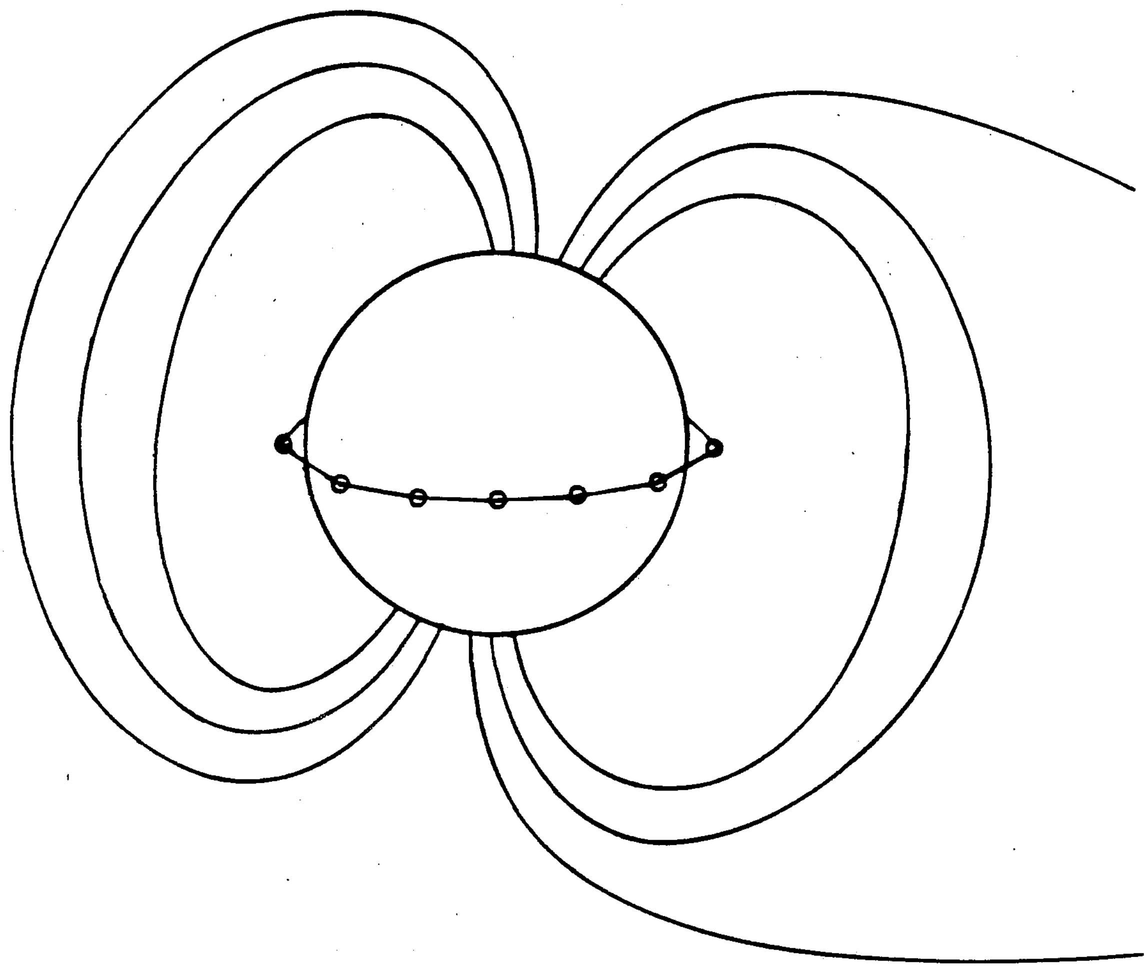

Fig. 1

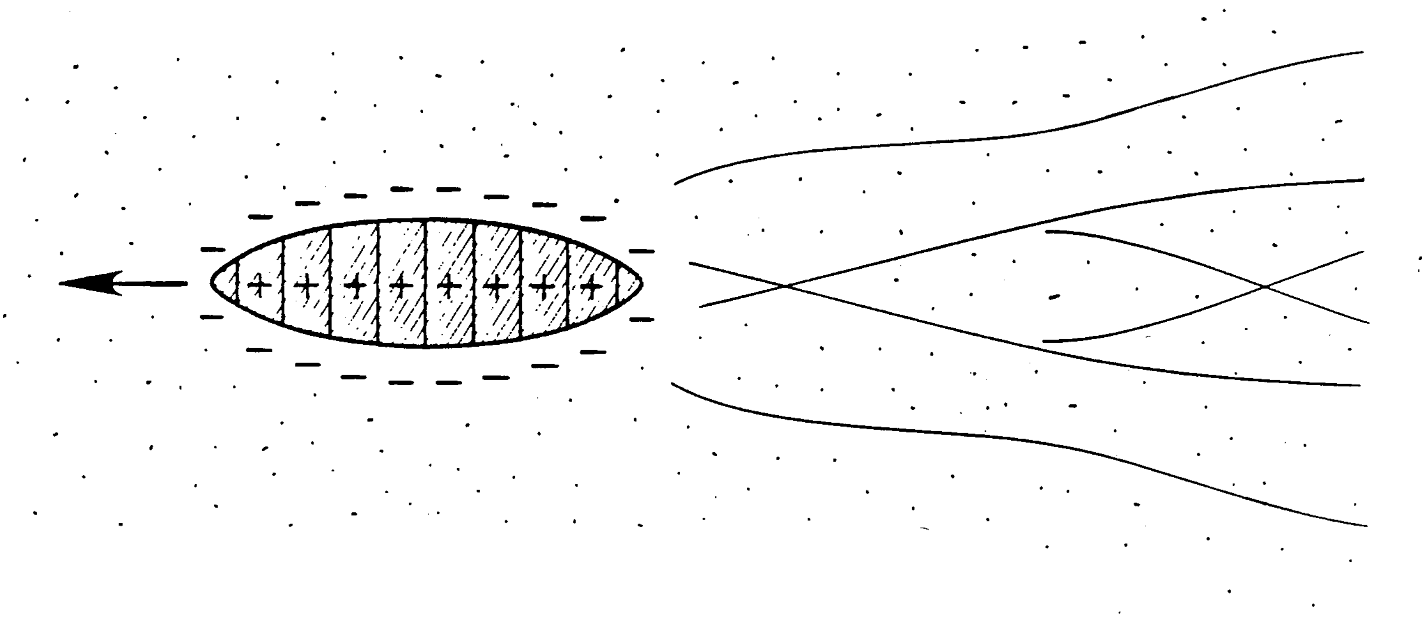

Fig. 2