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PROSPECTS OF THE SURFATRON LASER PLASMA ACCELERATOR

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1. Introduction

The surfatron laser-plasma accelerator[1,2] is an extension of the plasma beat wave accelerator scheme. In this concept, the limit on the energy gain of $2(\omega/\omega_p)^2mc^2$ of the particle in the plasma beat wave accelerator is overcome by imposing a B field of appropriate strength perpendicular to the plasma wave. This accelerates particles parallel to the phase fronts of the accelerating wave which keeps them in phase with it. Energy gains at the rate of 30 GeV/cm $[B_{KG}/n_{16}\lambda_\mu](1/\lambda_\mu)$ across the wave and of 0.1 GeV/cm $[B_{KG}/n_{16}\lambda_\mu](n_{16})^{\frac{1}{2}}$ in the direction of the wave are theoretically possible to arbitrarily large energies. In this paper, we assess the prospects of a 100 GeV accelerator based on the surfatron concept. The plasma wave is excited by small angle optical mixing which drastically reduces the required laser power and plasma size. Parameters for a possible proof-of-principle experiment are estimated.

2. The Surfatron Concept

A high phase velocity plasma wave is excited in the presence of a perpendicular magnetic field by beating two laser beams in a plasma such that their frequency difference is the upper hybrid frequency. Thus, $\Delta\omega = \omega_0 - \omega_1 = \omega_h = (\omega_p^2 + \omega_c^2)^{\frac{1}{2}}$, where ω_c is the nonrelativistic electron cyclotron frequency eB/mc. Consider a longitudinal plane wave electric field of the plasma wave propagating at $\underline{v}_{ph}$ and the applied magnetic field of the form

$$\underline{E} = E_0 \sin(kx - \omega t)\,\underline{a}_x \qquad (1)$$
$$\underline{B} = B\,\underline{a}_z .$$

A trapped particle in such a wave now experiences a $-\underline{v}_{ph} \times \underline{B}$ force which accelerates it parallel to the wavefront of the accelerating wave, while at the same time keeping it in phase with it. (Fig. 1) In the wave frame the x component of the Lorentz force is

$$F_x = e(E_0 \sin kx_1 + \gamma_{ph} v_y' B/c) \qquad (2)$$

where $\gamma_{ph} = (1 - v_{ph}^2/c^2)^{-\frac{1}{2}}$, $v_{ph} = \omega/k$, $x_1 = x - v_{ph}t$ and v_y' is the y velocity in the wave frame. The first term in the Lorentz force is the trapping term and the second term is the de-trapping or gyratory term. If the de-trapping force is smaller than the trapping force, $\gamma_{ph}B < E_0$, then a trapped particle can never become out of phase with the electric field and thus can be accelerated indefinitely.

By solving the equations of motion of a trapped particle of charge e and rest mass m in the laboratory frame

$$\frac{d(\gamma v_x)}{dt} = \frac{eE_0}{m} \sin(kx - \omega t) + \omega_c v_y \qquad (3)$$

$$\frac{d(\gamma v_y)}{dt} = -\omega_c v_x \qquad (4)$$

where $\gamma = (1 - v_x^2/c^2 - v_y^2/c^2)^{-\frac{1}{2}}$, Katsouleas and Dawson[1] have shown that the particle gains energy at a rate

$$\frac{\Delta u}{\Delta y} = 30\ \text{GeV/cm}\,[B_{KG}/n_{16}\lambda_\mu]\ 1/\lambda_\mu \qquad (5)$$

$$\frac{\Delta u}{\Delta x} = 0.1\ \text{GeV/cm}\ [B_{KG}/n_{16}\lambda_\mu]\ (n_{16})^{\frac{1}{2}}; \qquad (6)$$

theoretically to arbitrary energies. Here B_{KG} is the magnetic field in kilogauss, n_{16} is the plasma density in the units of 10^{16} cm^{-3} and λ_μ is the laser wavelength in microns. The quantity in the square parenthesis is the ratio of $\gamma_{ph}B$ to the critical or wavebreaking electric field, $E_{crit} = mc\omega_p/e$, which must be less than 1 by the trapping inequality; we will take it to be equal to 0.1. That the particles gain energy at a rate given by equations (5) and (6) has been confirmed both in single particle calculations and in fully self-consistent, relativistic simulations, using a 1 2/2-D electromagnetic particle code.[2] Several examples are presented in Table I for accelerating particles to 100 GeV. We will now discuss the example based on using 1-μm laser to show how we can hope to achieve such a device in practice.

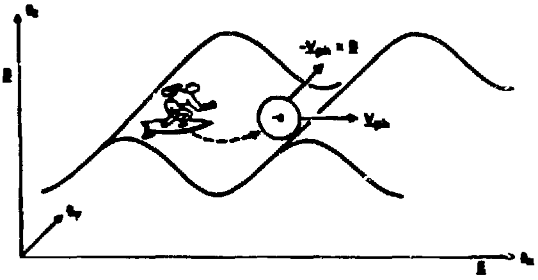

Figure 1. In the "SURFATRON" accelerator scheme a perpendicular B field is applied to the plasma wave such that an electron trapped by a potential trough moving at v_{ph} sees an electric field, $\gamma_{ph}v_{ph}B/c$, which accelerates it across the wave front.

TABLE I: Sample Parameters To Reach 100 GeV Based On The SURFATRON Concept

Laser Wavelength (μm)	10.6	1.06	0.26
Plasma Density (cm^{-3})	10^{18}	10^{19}	10^{20}
$[B_{KG}/n_{16}\lambda_\mu]$	0.1	0.1	0.1
Magnetic Field (kG)	100	100	260
Device width W (m)	3.3	0.33	8.7×10^{-2}
Device length L (m)	10	3.16	1
Angle Between Particles and Wave (degrees)	18.3	6	5

3. Laser Power Requirements

A rough estimate of the laser power required can be obtained from energy balance arguments. First, the longitudinal electric field, E_p represents an

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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED energy density

$$W_p = \frac{E_p^2}{8\pi} \sim 500\, n_{16}\, \varepsilon^2 \quad \text{Joules/cm}^3 \qquad (7)$$

where $\varepsilon = E_p/E_{crit}$. For the current example $\varepsilon = 0.1$ and $n_{16} = 10^3$, so $W_p = 5000\ \text{J/cm}^3$. To avoid significant pump depletion, the total energy in the laser pulse must be much greater than that in the plasma wave.

$$\left(\frac{E_L^2}{8\pi} + \frac{B_L^2}{8\pi}\right) \tau(\text{FWHM})\ c\ A \gg \frac{E_p^2}{8\pi} L\ A \qquad (8)$$

Here τ(FWHM) is the full-width at half maximum pulse duration, c is the group velocity of the light waves, L is the length of the system and A is the cross sectional area. Since the group velocity of the plasma wave, $3v_e^2/v_{ph} \ll c$, we have assumed that the laser pulse excites the plasma wave throughout our volume. The ratio of the longitudinal electric field to the laser field or the coupling efficiency is simply

$$\frac{E_p}{E_L} \sim \varepsilon\ \frac{c}{v_o}\ \frac{\omega_p}{\omega_L} \sim \varepsilon\ \frac{c}{v_o}\ \lambda_\mu \frac{\sqrt{n_{16}}}{300}. \qquad (9)$$

Combining (8) and (9) gives the laser intensity required as

$$\left(\frac{v_o}{c}\right)^2 \gg \frac{1}{2}\, \varepsilon^2\, \frac{L}{\tau(\text{FWHM})c} \left(\frac{\omega_p}{\omega_L}\right)^2. \qquad (10)$$

4. Finite Angle Optical Mixing[3]

It would at first seem an impossible task to excite a plasma that is 0.33 meters wide on laser power considerations alone, even if a 3.16 meter long ×0.33 meter wide plasma with the required homogeneity, at such high densities could be created. The problem therefore has to be tackled the following way. First, we have to keep the laser beams as small in diameter as possible to achieve the necessary intensities commensurate with achieving a reasonable Rayleigh length. Rayleigh length in this case has to be equal to or greater than half the device length. Second, we realize that the electron beam makes an angle with respect to the plasma wave in the laboratory frame. In this case, this angle is 6°. Now if instead of using colinear geometry for optical mixing, we utilize some finite angle optical mixing then (because $k_p \ll k_0, k_1$) we can considerably reduce the device width. (Fig. 2)

To calculate the geometry for optical mixing we have to realize only two constraints. First, the only region of the plasma that we need to excite is the region traversed by the electron beam. We therefore propagate our high frequency beam focussed tightly along this path. Second, in this region $\underline{k_p}$ makes an angle of 6° with respect to the high frequency beam $\underline{k_0}$. We now use energy and momentum conservation conditions to calculate the angle between the two laser beams. In the present example the angle between $\underline{k_0}$ and $\underline{k_1}$ turns out to be only 0.5°. Over the device length of 3.16 meters the two laser beams diverge by only 4.4 cm. This we take to be the width of the low frequency beam. Thus for a 100 GeV accelerator using a 1 μm laser we are talking about a plasma that is around 3 mm in diameter and a few meters long. By reducing the width (r) of the high frequency beam, we also help to reduce the beam emittance which is roughly on the order $4(r^2/R^2)\pi$ steradian for the highest energy particles, $R^2 = W^2 + L^2$. The energy spread, $\Delta\gamma/\gamma$, of the accelerated particles should also be excellent since the energy gain of the particles is much larger than γ_{ph}, their initial energy.

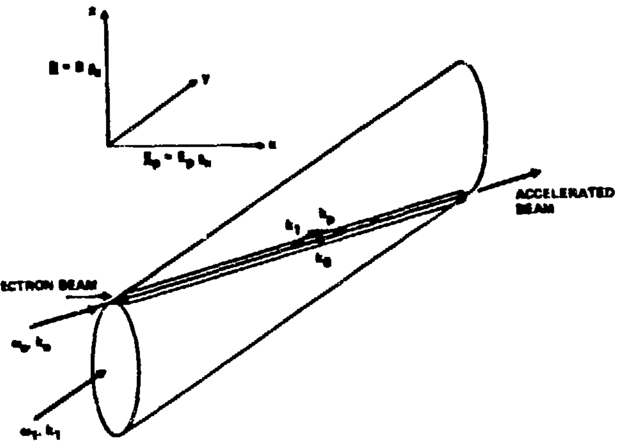

Figure 2. In the "SURFATRON" concept the injected particles are accelerated at an angle w.r.t. the plasma wave. Optical mixing at a small angle must be employed such that the high frequency laser beam and the electron beam are colinear. In the wave frame the electrons move parallel to the plasma wave fronts.

The laser pulse length determines the amount of laser energy that is required. An advantage of using a short pulse is that the plasma should be stable against many undesirable instabilities that occur on ion-acoustic timescale: ponderomotive, thermal and resonant self-focussing, and Brillouin scattering. Another advantage of using a short pulse is that the main body of the plasma will remain relatively unperturbed. Simulations show that propagation of an intense ($v_o/c \sim 1$), modest length (100 ps) laser pulse through an underdense plasma can heat the plasma up to hundreds of keV temperatures due to non-linear wave-wave and wave-particle interactions. On the other hand, too short a laser pulse implies a very short bunch length and consequently poorer luminosity. Using our particle simulations as a guide we feel that a laser pulselength on the order of a few picoseconds is a reasonable compromise.

In the example then, suppose that by using $F/10^3$ optics we can focus a 1 μm laser beam to a 1 mm spot size over the required length (~3 meters). Then to satisfy the laser power required (Eq. 10) we need ≫ 7.5 kJ of laser energy in a 10 ps pulse. The low frequency beam is spread out over a much larger area, 44 × 1 mm²; however, it can be up to an order of magnitude less intense since it simply acts to seed the plasma wave with the appropriate $\underline{k_p}$. Thus we need roughly 33 kJ in this beam. We have neglected any collisional absorption of laser light by the plasma.[4] Since the electron-ion collision frequency $\nu_{ei} \propto 1/(T_e + mv_o^2/2)^{3/2}$ this is a reasonable assumption at very high intensities used in this scheme. Unfortunately, laser systems developed for laser fusion operate in typically 0.5-3 ns pulselength regime. Thus, considerable R and D effort is necessary in the area of high brightness, short-pulse lasers and focusing, transporting and manipulating such beams, specifically related to high energy accelerator needs.

5. Luminosity

The number of accelerated particles can also be estimated from considerations of energy balance.

$$N = \frac{\text{(Laser energy)(Coupling efficiency)}}{\text{(Energy/particle)}} \; \frac{\text{Particle energy}}{\text{Wave energy}} \qquad (11)$$

In this example we might expect to obtain 10^{10} particles at 100 GeV assuming the ratio of (particle energy/wave energy) to be 0.5. Such a low number of accelerated particles does not lead to a very useful luminosity. For colliding beams the luminosity can be estimated using,

$$L = N^2 f/4\pi\sigma_x\sigma_y \quad \mathrm{cm}^{-2}\mathrm{s}^{-1} \qquad (12)$$

where f is the repetition rate and $(\sigma_x\sigma_y)^{\frac{1}{2}}$ is the r.m.s. transverse dimension of the colliding bunch. If we assume that f=1 and $(\sigma_x\sigma_y) = 10^{-6}$ cm^2 then we might expect a luminosity of $\sim 10^{25}$ cm^{-2}s^{-1}. This is what we might expect in a proof-of-principle type experiment and is not to be considered as a fundamental limit on luminosity in the surfatron scheme.

6. Conclusion

In this paper the surfatron concept is proposed as a possible solution to the problem of staging in the laser-plasma beat wave accelerator scheme. Prospects of a 100 GeV particle accelerator based on the surfatron concept are explored. Finite angle optical mixing appears to be a promising solution for drastically reducing the width of the plane wave, thereby, making the required laser power and the device size realizable for a proof-of-principle experiment. Our conclusions are based mainly on analytical theory and one-dimensional particle simulations. We are presently carrying out two-dimensional simulations in order to investigate transverse stability, self-consistent B field generation and sidescattering problems. The most severe of these problems appears to be the self-induced B field which is seen in 1-D simulations and arises because of the oscillatory motions of the untrapped electrons across the wavefronts. Experimentally, of course, the major problem is going to be one of producing a homogeneous plasma in the presence of a perpendicular magnetic field. Laser ionization of a laminar gas jet from a supersonic nozzle is one possible solution. However, before we can contemplate building a 100 GeV laser accelerator based on the surfatron concept considerable effort is necessary on the development of appropriate plasma sources and very short pulse laser systems.

7. Acknowledgements

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8. References

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