DOUBLE BEAT-WAVE MECHANISM TO KEEP PARTICLE
IN PHASE WITH ACCELERATING PLASMA WAVE

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ABSTRACT

Two mechanisms are described by which the phase matching between accelerated particle and accelerating plasma wave in a plasma beat-wave accelerator can be maintained indefinitely. 1) Interference between two beat-waves to cancel a) the fields in the interfering electromagnetic waves, b) electron oscillations which would otherwise be set up by those waves. 2) Alternating plasma density used in conjunction with one or two beat-waves.

INTRODUCTION

The potential well which accelerates particles in a plasma beat-wave accelerator,⁽¹⁾ moves with a speed

$$v_g = c(1 - (\omega_p/\omega)^2)^{1/2}, \quad (1)$$

where ω_p is the plasma frequency, and ω is the frequency of the electromagnetic wave which sets up the plasma oscillations, which in turn generate the accelerating potential. Particles with speeds $v > v_g$ will eventually overtake the potential well, and that puts an upper limit on the energy they can acquire. This limitation can be overcome by the proposed surfatron mechanism^(2,3) in which the particle trajectory makes an angle $\theta \neq 0$ with the line along which the potential well travels. Two difficulties arise in connection with the surfatron mechanism. First, for $\theta \neq 0$ the potential well will tend to curve the particle trajectory. To compensate for that, one has to impose an external magnetic field. Second, since the particle velocity has a component parallel to the plasma wave front, the transverse size of the accelerator has to be larger than if $\theta = 0$ were to hold, and in addition, some of the electromagnetic wave energy will be wasted. The second difficulty can be significantly alleviated through the ingenious device of "transverse optical mixing."⁽⁴⁾

Two alternatives to the surfatron mechanism will be described in the present note. Both insure continuing phase matching between the accelerated particle and the accelerating plasma wave. In both mechanisms phase matching is maintained even if the particle and plasma wave travel parallel to each other ($\theta = 0$), and in neither mechanism is an external magnetic field required.

DOUBLE BEAT-WAVE MECHANISM

To insure continued phase matching through this mechanism, one uses not one but two beat-waves. These beat-waves are arranged so that they interfere constructively whenever the particle is in phase with the accelerating potential well created by both of them. On the other hand, when the particle gets out of phase with the potential well

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created by, say, the first beat-wave, the second beat-wave will tend to cancel the effect of the first one, so that the effect of deceleration will be correspondingly reduced. The particle will then be allowed to essentially drift through these regions until it again gets into phase with the accelerating potential, where it will be accelerated further, etc.

Choose four electromagnetic plane waves of equal amplitudes, A , and equal polarization state, all traveling parallel to the z axis, which is also the direction of motion of the accelerated particle. Let all four waves be in phase, with the electric field maximum at $t = 0$ and $z = 0$. Denote the circular frequency of the i th wave by ω_i ($i = 1, 2, 3, 4$), the electron density in the plasma by ρ_e , and the plasma frequency by ω_p . Choose

$$\omega_1 - \omega_2 = \omega_p \quad (2a)$$

$$\omega_3 - \omega_4 = \omega_p \quad (2b)$$

$$\omega_3 - \omega_1 = \Delta\omega, \quad (2c)$$

The $\Delta\omega$ is to be specified later. With this choice the first two waves will set up a beat-wave with beat frequency ω_p , and so will the third and fourth wave.

Assume, as usual for plasma beat wave accelerators, that $\omega_p/\omega_i \ll 1$, for $i = 1, 2, 3, 4$. Then the phase velocity of the plasma wave set up by an electromagnetic wave pulse will equal the group velocity of that pulse.⁽¹⁾ Denote the group velocity in the plasma of the first and second beat-wave by v_{g1} and v_{g2} respectively. The wave vector of the plasma wave set up by the first and second beat-waves, respectively, will be

$$\begin{aligned} k_{p1} &= \frac{\omega_p}{v_{g1}} \approx \frac{\omega_p}{c} \left(1 + \frac{1}{2} \left(\frac{\omega_p}{\omega_1} \right)^2 \right) \\ k_{p2} &= \frac{\omega_p}{v_{g2}} \approx \frac{\omega_p}{c} \left(1 + \frac{1}{2} \left(\frac{\omega_p}{\omega_1 + \Delta\omega} \right)^2 \right). \end{aligned} \quad (3)$$

We will refer to the beat-wave between the two beat-waves as "super beat-wave." The amplitude (envelope) of the super beat-wave varies as

$$\begin{aligned} |A_s| &= 4|A\cos \frac{1}{2} [(\omega_1 - \omega_3)t - (k_1 - k_3)z]| \\ &\approx 4|A\cos \frac{1}{2} \{(\Delta\omega)t - \frac{\omega_p}{c} \frac{1}{2} \left[\left(\frac{\omega_p}{\omega_1} \right)^2 - \left(\frac{\omega_p}{\omega_1 + \Delta\omega} \right)^2 \right] z\}| \\ &\xrightarrow{\Delta\omega/\omega_1 \rightarrow 0} 4|A\cos \frac{1}{2} \left\{ \Delta\omega \left[t - \left(\frac{\omega_p}{\omega_1} \right)^3 \frac{z}{c} \right] \right\}|. \end{aligned} \quad (4)$$

If the accelerating potential well is L_+ long and travels with a speed v_g (all quantities in this paper are measured in the laboratory frame), then the time it takes for a particle with speed v to move across the accelerating potential well, from one end to the other, is $t_L = L_+/(v - v_g)$. The distance the particle travels in the plasma during this time is

$$L = L_+ \frac{v}{v - v_g}, \quad (5)$$

assuming v is essentially unchanged during the process.

We describe two distinct methods to realize the double beat-wave mechanism.

a) In the first method $\Delta\omega$ is chosen so that while the particle travels a distance L , one half of a complete super beat-wave period passes over its

$$\pi = (\omega_1 - \omega_3)t_L - (k_1 - k_3)L. \quad (6)$$

Let λ_{b1} be the wavelength of the plasma wave generated by the first electromagnetic beat-wave. Assume $L \gg \lambda_{b1}$. Then to insure condition (6), one needs

$$\Delta\omega = \pi \frac{v - v_g}{2L_+} \left\{ 1 - \left(\frac{\omega_p}{\omega_1} \right)^3 \frac{v}{c} \right\}^{-1}. \quad (7)$$

To illustrate, consider the case when $\omega_1 = 1.88 \cdot 10^{15} \text{ sec}^{-1}$, $\omega_p = 5.64 \cdot 10^{13} \text{ sec}^{-1}$, and $v \approx c$. Then $t_L = 2.5 \cdot 10^{-10} \text{ sec}$, $L = 7.8 \text{ cm}$, and one needs: $\Delta\omega = 1.27 \cdot 10^{10} \text{ sec}^{-1}$, so that $\Delta\omega/\omega_1 = 6.8 \cdot 10^{-6}$.

b) In the second method one chooses $\Delta\omega$ to be such that while the particle travels a distance $2L$, the second beat-wave moves ahead of the first one by a distance λ_{b1} :

$$\pi = (k_{p1} - k_{p3})L. \quad (8)$$

Then if the two beat-waves are in phase when the particle is inside an accelerating potential well, then they will again be in phase when the particle reaches the next potential well. Halfway between those two events, however, the effect of the two beat-waves cancel, which tends to eliminate any deceleration which would otherwise occur.

As an illustration again choose ω_1 , ω_p and v as in the example given under a). Then from Eq. (8) one finds $\Delta\omega = 0.779 \cdot 10^{15} \text{ sec}^{-1}$, i.e. $\Delta\omega/\omega_1 = \sqrt{2}$.

This method generally requires higher $\Delta\omega/\omega_1$ values than the method described under a), that feature is sometimes desirable.

When method b) is used, the common polarization of the waves with circular frequency ω_1 and ω_2 may differ from the common polarization of the other two waves.

ALTERNATING DENSITY (DOUBLE BEAT WAVE) MECHANISM

In this mechanism the plasma is subdivided into regions with different electron densities. In regions of the first type the electron

density is ρ_{eA} , while in regions of the second type, the density of electrons is ρ_{eB} . We will refer to regions of the first and second type as A-regions and B-regions respectively. The plasma frequency in the A-regions and B-regions will be denoted by ω_{pA} and ω_{pB} respectively. Choose two electromagnetic plane waves with equal amplitudes, and equal polarization, travelling along the z axis. Let their frequencies, ω_1 and ω_2 satisfy

$$\omega_1 - \omega_2 = \omega_{pA} \quad (9a)$$

These two waves will set up a beat-wave which will generate resonant electron oscillations in any region-A. On the other hand, if ρ_{eA} and ρ_{eB} are sufficiently different, then this same beat-wave cannot set up resonant electron oscillations in any B-region. Choose the length of any A-region to be L, corresponding to the value of v at the time when the particle passes through that region. Then if the beat-wave is correctly phased relative to the particle, it will continuously accelerate it while the particle moves across the A-region. As the particle leaves the accelerating potential well, and would enter a decelerating well, the particle enters a B-region where it experiences no significant acceleration, drifts through this region, enters the next A-region where it is accelerated further, etc.

One can improve the above scheme by utilizing two more electromagnetic plane waves with equal amplitudes and polarization, both travelling along the z axis. Choose their frequencies according to

$$\omega_3 - \omega_4 = \omega_{pB} ,$$

and Eq. (2c). These two waves will set up a second beat-wave which will generate resonant electron oscillations in any B-region, but not in the A-regions. If the second beat-wave is correctly phased relative to the particle, it will accelerate it across B-regions. Thus the two beat-waves together with the alternating plasma density, will insure continuous particle acceleration while the particle moves along the entire length of the plasma beat-wave accelerator.

The common polarization of the first two electromagnetic waves need not be the same as the common polarization of the other two.

In all the schemes discussed in this note, care must be taken to choose $\Delta\omega$ so that except for the wanted frequencies, no other beat frequency between the various waves should overlap with any resonant frequency regions of the plasma.

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