Collective Acceleration Processes Using Waves on Electron Beams

by

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Abstract

We present, in this review, a summary of the various mechanisms which have been proposed for the acceleration of electrons and ions in waves carried on electron beams. This review attempts to highlight the physical processes occurring in these accelerators and, where appropriate, points out the clearly defined limits of applicability.

Introduction

In this paper we review the principles of collective acceleration, using waves carried on an electron beam, and briefly examine some of the limitations of this technique when applied to the generation of ultra-high energy beams.

The basic objective of collective acceleration is to use a high current, moderate energy electron beam to generate a lower current, high energy beam. A subsidiary requirement is that the accelerator be compact; that is, we maintain a high average field gradient throughout the accelerator. Wave accelerators, such as those described below, form a subset of collective accelerators in which particle acceleration is achieved by a two step process. Typically a wave is grown on an electron beam by means of the interaction between the electron beam and some external structure, such as a disk loaded waveguide or a tape helix. The beam is extracted from the wavegrowth region and injected into an inhomogeneous drift region where the phase velocity of the wave is increased in a controlled fashion such that a particle initially trapped in the beam supported wave will continue to be trapped and accelerated with the wave. From the point of view of the purist this does not constitute a true collective accelerator, since the waves and the particles would be self synchronized in such a device. It is probably true that if the maximum benefit is to be derived from a collective accelerator then the self synchronization feature should be present. The approaches described in this paper do not have this feature and control of the acceleration gradient must be provided by external means.

A number of variations of the wave accelerator have been suggested and some have been attempted experimentally, albeit at very low energies, in order to demonstrate the principle of the accelerator. In most cases the objective has been ion acceleration, although in some cases the technique is equally applicable to electron acceleration. In the case of ion acceleration the ions are confined radially by the space charge fields of the unneutralized electron beam which, in turn, is confined by a strong axial magnetic field. For the electron accelerator the applied magnetic field also confines the beam being accelerated to high energy.

There are two main regimes of interest for collective acceleration, namely:

a. The particles being accelerated have a lower terminal velocity than the beam electrons, and

b. The particles being accelerated have a final velocity greater than that of the beam electrons.

In the former case we are usually concerned with ion acceleration to a maximum energy equal to or less than the rest mass of the particle being accelerated, expressed in units of the electron rest mass, times the kinetic energy of the electrons in the primary beam. In this case the acceleration process will probably involve the use of a slow wave carried on the beam (i.e. one having a velocity less than that of the electrons in the beam). This situation is one in which we deal with a negative energy wave interaction so that both the wave and particle energies increase throughout the accelerator. The energy source for the acceleration is the drift energy of the primary electron beam. In the second case we consider either electron or ion acceleration. The acceleration occurs as the result of an interaction between the particles and a beam fast wave. Usually this is accomplished as the result of the non linear interaction between two waves in which a beat wave is generated and used for particle acceleration.

Up until the present programs concerned with collective acceleration using beam waves have been centered on the use of slow waves.[1,2,3,4] This topic will form the major part of this paper. In addition to this the principles of beat wave accelerators, using a modulated beam propagating through a rippled magnetic field or a periodic structure, will be discussed. In either case the variable phase velocity of the beat wave is achieved by slowly varying the period of the passive structure.

Fundamentals of Beam Supported Wave Accelerators

(1) Slow Wave Accelerators

Two basic wave types have been employed in slow wave accelerators, namely cyclotron and space charge waves. In an infinite medium the dispersion relations for these waves take the form:

$$\text{Cyclotron Waves:} \quad \omega = kv - \Omega$$

$$\text{Space Charge Waves:} \quad \omega = kv - \omega_p$$

In these relations ω and k are the wave frequency and wavenumber respectively. Ω and ω_p denote the electron cyclotron and plasma frequencies. These relations represent oscillations at the cyclotron and beam plasma frequency in the beam frame, which have been Doppler shifted to the laboratory frame. In a finite system not all of the electric field lines in the space charge wave mode are purely axial, and there are a number of field lines which finish on the tube walls. The radial electric field and the corresponding azimuthal magnetic fields give rise to an electromagnetic component of the otherwise purely electrostatic oscillation. The correct form of the space charge wave dispersion relation in a bounded medium is given below:

$$\omega = k_z v - \omega_p \left[\frac{k_z^2 c^2 - \omega^2}{k^2 c^2 - \omega^2}\right]^{1/2}$$

In this relation k_z represents the axial component of the wave number. k is defined by the relation

$$k^2 = k_z^2 + k_\perp^2$$

where $k_\perp$ is the perpendicular component of the wave number. In contrast to this situation the cyclotron wave is essentially unaltered by the presence of conducting boundaries so that the dispersion relations take the form shown in figure 1.

Both the cyclotron wave and the space charge wave accelerators rely on the excitation of large amplitude waves on a relativistic electron beam immersed in a strong axial magnetic field, which is required to radially confine the electrons. Ions are injected into wave train and are accelerated as the result of an adiabatic change in the phase velocity of the wave. This process is shown schematically in figure 2 where a change in the characteristic frequency of the primary beam (cyclotron or plasma

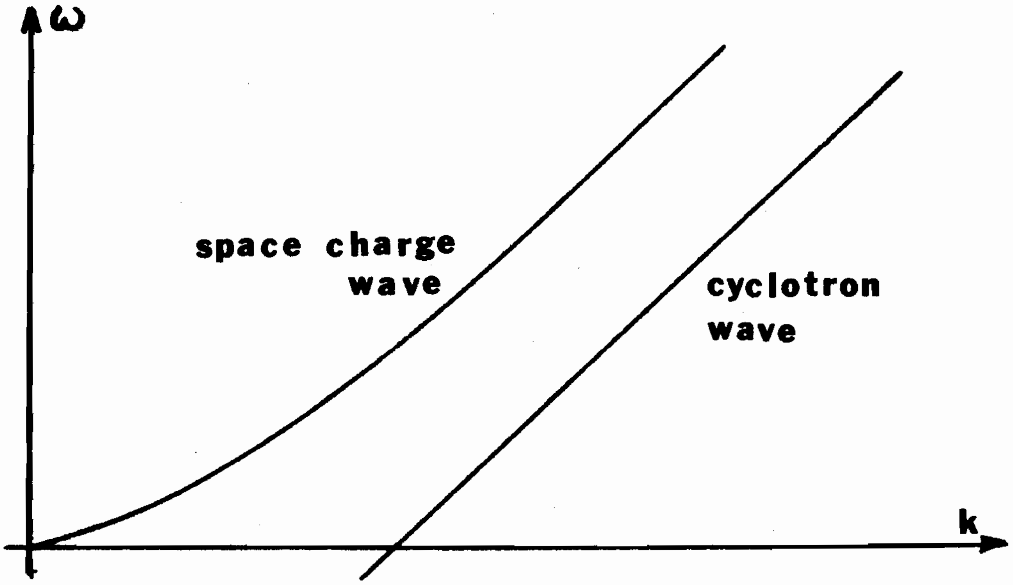

Fig. 1 Dispersion relations for the slow space charge and cyclotron waves

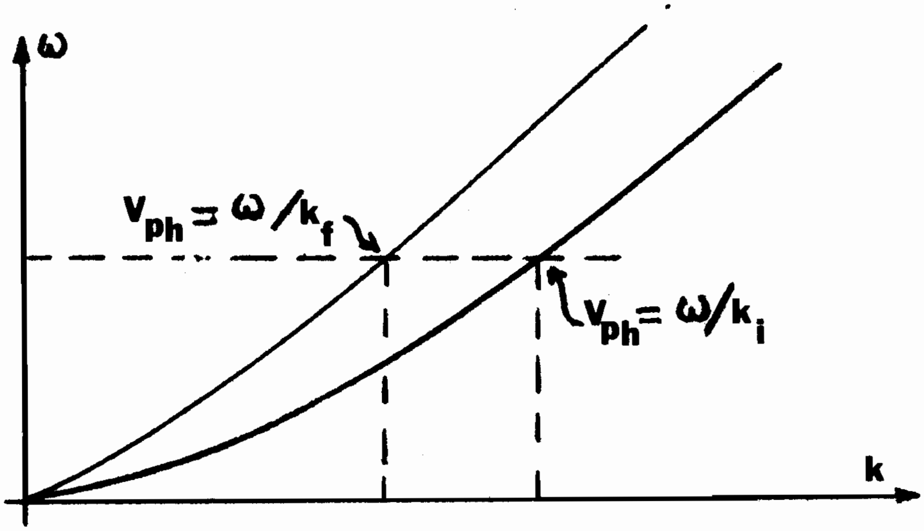

Fig. 2 Principle of ion acceleration in a slow space charge wave

frequency) leads to a shift from the right to the left dispersion curve. An adiabatic change in the beam properties ensures that the change will occur at constant wave frequency. In the case of the cyclotron wave, acceleration is accomplished by a change in the applied magnetic field used to guide the beam. This, of course, requires a flaring out of the guide, since the electrons will expand following the reduction in the applied magnetic field. For the space charge wave the acceleration process requires an adiabatic change in the electron beam plasma frequency. This could also be achieved by an expansion of the beam in a flaring guide and magnetic field, but the preferred method of decreasing the effective plasma frequency uses a slowly converging guide and a uniform externally applied axial magnetic field. This is preferred as it permits one to retain a well defined constant radius electron beam. This is clearly advantageous if staging is required for the electron beam. The reduction in tube diameter leads to a reduction in the effective plasma frequency, since it leads to a greater number of field lines finishing on the tube wall. This increases the electromagnetic component of the wave. Alternately it is evident that a reduction in the tube size will lead to an increase in the perpendicular wave number. The successful implementation of a wave accelerator requires that at least four conditions be satisfied:

(i) Successful wavegrowth to the required amplitude,

(ii) Adequate wave coherence, wave propagation and phase velocity control,

(iii) Development of a suitable ion injector for the wave, and

(iv) Successful trapping of the ions.

We now address each of these topics in somewhat greater detail.

Wavegrowth

The cyclotron wave is essentially a TE mode and the space charge wave a TM mode. The art of growing these waves on beams is at a substantially different level for the different modes. The cyclotron mode has an axial r.f. magnetic field and therefore needs a structure such as a tape helix for its excitation. Work has been carried out in both the U.S.A. and in the U.S.S.R. to investigate the growth of a slow cyclotron wave. Most of this work is, as yet, unpublished. The required mode has been successfully grown on a low power, low energy, electron beam[5] although considerable difficulty has been experienced in the growth of the correct mode on a high power beam under conditions when the beam temperature is sufficiently low. For higher temperature beams (greater spread in the transverse components of the beam energy) the excitation is readily achieved but involves bootstrapping from an unwanted plasma oscillation mode.

The excitation of the slow space charge wave is well developed and uses the self excitation in disk loaded waveguides.[3] This same mode has been utilized in microwave systems for many years. Concurrent with the excitation of the lowest order axially symmetric mode there is excitation of higher order axially symmetric modes. To date no effort has been made to suppress these unwanted modes as they have phase velocities well away from the particle velocities and have not interfered with the experiments in progress. Microwave tube technology exists which should permit suppression of these modes if the need arises.

Wave Coherence, Transport and Phase Velocity Control

All experiments carried out to date have used short duration pulses (~50-100 nsec.) and coherent waves, with bandwidths limited by the pulse duration, have been observed over the complete pulse width.[6] Similarly measurements of the wave transport over the short experimental lengths used to date (3 m.) have not uncovered any great difficulties. The technique employed for the control of the wave phase velocity is considerably simpler for the cyclotron wave than that required for the space charge wave. This arises mainly as the present test experiments are all carried out at very low wave phase velocities ($\lesssim 0.2$ c). In this regime the space charge wave phase velocity changes extremely rapidly with the changing plasma frequency. In fact it has been shown analytically that the wave phase velocity only goes to zero when the beam current approaches its vacuum limit (set by space charge), and further only when the wave frequency and wavenumber tend to zero. For practical purposes, in the linear regime, the wave phase velocity approaches a limit of order 0.2 c to 0.25 c. For both waves, however, the phase velocity has been observed to change as predicted with changes in the cyclotron (albeit in the presence of a simultaneously excited plasma wave) or effective plasma frequencies. There is, at present, an inadequate base to confirm the wave velocity change in an actual accelerator geometry. All measurements have been made, to date, in homogeneous guides under varying shot to shot conditions of the beam and field parameters. The change in wave parameters in an inhomogeneous guide or in a flaring magnetic field are not yet adequately confirmed, although there is evidence to suggest that the dependence is correct in at least the converging guide space charge wave configuration.

Ion Injection and Trapping

For the purpose of demonstration of the proof of principle of slow wave accelerators an adequate source of ten MeV protons has been developed[7] and used in initial experiments on the slow space charge wave accelerator.[8,9] Cyclotron wave accelerator programs have not been reported at the level where ion injection was needed. In neither case has ion trapping and acceleration been reported although work is currently in progress on this topic. These topics have not been addressed from the point of view of high energy physics. Obviously adequate sources of high energy protons exist, although they are probably too weak to make full use of the high current capability of a collective accelerator.

(2) Beat Wave Accelerators

An alternate class of collective accelerators using waves on beams rely on the non linear interaction between a modulated electron beam and a quasi-periodic structure to generate a beat wave, which may be used to accelerate either ions or electrons. Two experimental configurations have been described in the published literature, namely modulated beam propagation through a rippled magnetic field, and modulated beam propagation through a waveguide having a rippled boundary. In both cases the beat wave phase velocity is controlled by a slow change in the period of the passive structure. This situation is one where a 'fast wave' interaction can be produced as the result of the beating of two slow waves. This situation is extremely similar to that obtained in the plasma wave accelerator described elsewhere in these proceedings.[10] In that case however, two waves each having a phase velocity greater than the speed of light, beat to produce a wave having a velocity less than the speed of light in vacuum. We now outline the underlying theory of the rippled wall beat wave accelerator.[11,12]

Consider a pencil beam propagating through a waveguide having a slowly varying radius R(z). If the beam current is I, the electron velocity β c, and the beam radius r (assumed constant as the result of an applied uniform homogeneous guide magnetic field), then the potential on axis may be expressed in the form[13]

$$\Phi(z,t) = \left(\frac{I}{\beta c}\right)\left\{1+2\ell r\left(\frac{R(z)}{r}\right)\right\} .$$

Expressing the boundary of the guide in the form

$$R(z) = R\{1+\xi_0 \sin k_1 z\} ,$$

and the modulated beam current as a travelling wave

$$I(z,t) = I_0\{1+\xi_2 \sin(k_2 z-\omega t)\}$$

where ξ_0 and ξ_2 denote the modulation coefficients for the boundary and the beam current we obtain, after some algebra, the following expression for the electric field on the tube axis

$$E_z(z,t) = \left(\frac{I_0}{\beta c}\right)\left[1+s\ell r\left(\frac{R}{r}\right)\right]\{\xi_1 k_1 \cos(k_1 z)+\xi_2 k_2 \cos(k_2 z-\omega t)$$

$$- \frac{\xi_1 \xi_2}{2}(k_1-k_2)\sin[(k_1-k_2)z+\omega t] + \frac{\xi_1 \xi_2}{2}(k_1+k_2)\sin[(k_1+k_2)z-\omega t]$$

In this expression ξ_1 represents

$$\xi_1 = \frac{2\xi_0}{\left[1+2\ell r\left(\frac{R}{r}\right)\right]}$$

The terms of interest in this equation are the two beat wave terms which represent forward and backward waves. The forward wave has a phase velocity limited to the propagation velocity of the modulated beam, whereas the backward wave has a range of velocities from zero to infinity depending on the choice of the ripple period L relative to the wavelength λ of the modulated beam. An additional branch of the forward wave occurs for $L > \lambda$. The relevant phase velocities are

$$v_{pL} = \frac{\omega}{k_2}\left[\frac{L}{L \pm \lambda}\right]$$

Experiments have been carried out to investigate operation in both the forward and backward wave modes. In the former case the accelerated particle would be an ion, whereas the backward wave could be used to accelerate either ions or electrons. Velikov[11] has demonstrated successful operation for ion acceleration in a pilot experiment in which various ions were accelerated by several kilovolts. Friedman[14] has carried out a study of the rippled field accelerator for electrons using the backward wave. In this case the physics is essentially identical to that described above. He modulated the primary electron beam using a series of coaxial cavities obtaining essentially a 100% modulation of the beam. A counter-streaming weaker electron beam was fed into the rippled field structure coaxial with the primary beam. Unfortunately the two beams did not propagate through each other so that the concept could not be tested. In this case this limitation may well have arisen as the result of the potential depression on axis, due to the space charge in the primary and secondary beams exceeding the value causing virtual cathode formation. None the less the concept seems sound and worth continued investigation.

Application to High Energy Physics Accelerators

The use of slow waves for collective acceleration implies that we are dealing with ion accelerators. In this application, and for a single stage accelerator, the ion energy is limited to

$$T = \frac{M}{m}(\gamma_e - 1)mc^2$$

where M and m represent the ion and electron rest masses respectively, and γ_e the relativistic factor for the electrons in the primary electron beam. This limit arises because the slow wave must propagate at a velocity not exceeding that of the electrons in the primary beam. Based on present day technology for intense electron beams this limit occurs at about 100 GeV. and would require the use of the ATA[15] accelerator. Since this is an induction linac machine the peak output energy limit of 50 MeV is not fundamental and could in principle be increased to an arbitrarily large value. The propagation of the electron beam through each accelerating cavity does cause some increase in the beam emittance. Limitations imposed by this process, for possible application to ion acceleration, are not known.

In practice one need not be content with a single stage accelerator, i.e. one in which the ions are continually accelerated from low energy to their final energy, but can use a multi-stage acceleration system. In such a device each stage would extend over a short distance, of order a few meters, and ion motion would not be completely matched to the wave motion. If the wave electric field is slightly too large to obtain exact phase matching between the ion and the wave, then a fractional wavelength slippage of the wave in a single section can be used to advantage. The slippage in one stage can then be recovered at the start of the next stage. By this process the peak energy limitation given above can be relaxed and application of slow wave collective ion acceleration to high energy acceleration seems possible. This possibility is discussed in more detail by Denis Keefe[16] later in these proceedings.

A question of some significance in the wave accelerator is the average field gradient which can be maintained. The useful limit on this would appear to be set by self trapping of the electrons in the wave. This process starts at a field strength of order

$$E_z \sim \alpha k_z \frac{\left(\gamma_{ew} - 1\right)}{\gamma_{ph}} \frac{mc^2}{e}$$

where

$$\gamma_{ew} = \gamma_e \gamma_{ph} (1 - \beta_e \beta_{ph})$$

and γ_{ph} is the relativistic factor appropriate to the wave velocity. α is a numerical factor which could be of order ten[2]. At low phase velocities this limit is unimportant and field strengths of several hundred MeV/m are possible. At high energy the self trapping field onset occurs at field strengths of order

$$E_z \sim \frac{\alpha k_z}{\gamma_{ph}} \frac{(\gamma_e - \gamma_{ph})^2}{2\,\gamma_e \gamma_{ph}} \frac{mc^2}{e}$$

This relation implies, for high energy applications, that we should work at high electron kinetic energy and wave frequency, while maintaining γ_{ph} as low as possible consistent with being able to attain the final required energy. Detailed calculations of the phase slip per section permissible have not been performed. It is, however, of interest to speculate on wave parameters achievable at high energies. For the ATA electron beam $\gamma_e = 100$. At a wave $\gamma_{ph} = 25$ one can maintain an electric field of order 9×10^7 V/m at a wave frequency of 20 GHz. Electric fields within a factor of five of this have been achieved on a 5 MeV electron beam, albeit in a propagating TE mode. It would be of interest to carefully calculate the minimum value of γ_{ph} needed for an ultra high energy machine and to determine if this is sufficiently low, when phase slippage per module is permitted, to allow one to maintain the high average wave fields indicated above.

The use of beat waves for acceleration to high energy permits operation in two regimes, namely the backward wave and the upper forward wave branches shown in figure 3. In either case one generates a beat wave having an arbitrarily large velocity so that the limits described above for the slow waves are not applicable. In a beat wave accelerator one can consider acceleration of either protons or electrons, and experiments are in progress trying to demonstrate acceleration of both species of particle. Since the processes involved are inherently non linear it is more difficult to obtain a realistic estimate of the potential of the beat wave system. In the absence of other non-linear effects the accelerating electric field strength of the beat wave scales qualitatively as the product of the beam modulation and the modulation of the periodic

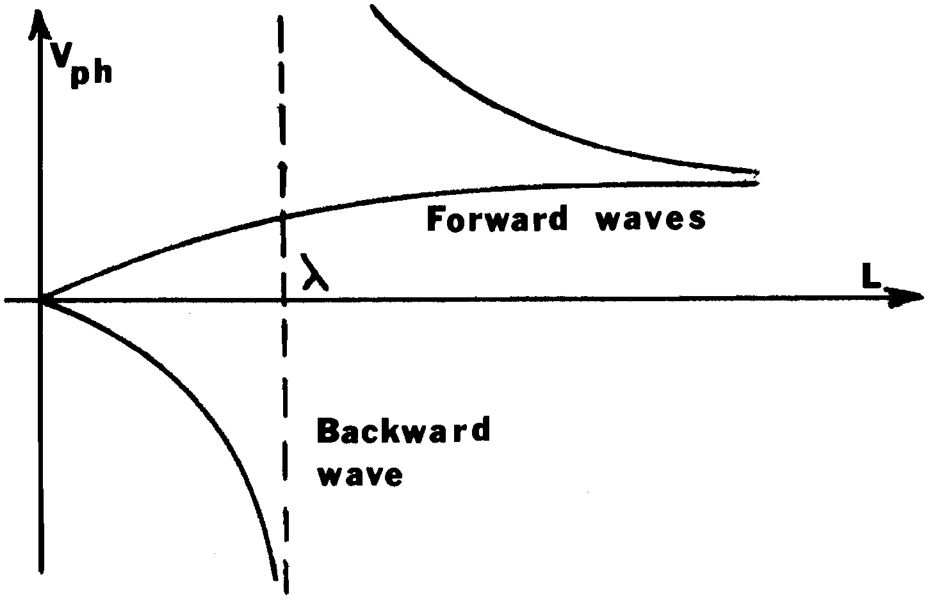

Fig. 3 Phase velocity of beat waves as a function of the period of the passive structure

structure. In principle both of these can be made large and it would seem that field strengths comparable to the self fields of the beam are achievable. Note that the self trapping limits indicated above should not be a serious problem in the beat wave accelerator because the phase velocity of the pump wave can be maintained well away from the electron beam velocity. More theoretical analysis of these waves is needed in order to make a serious determination of their potential for application to particle accelerators.

Conclusions

Wave accelerators based on the concepts outlined above hold some promise for application to high energy physics. Basically they offer two advantages:

(i) Average accelerating fields of order of the self fields of the beam are fairly readily achievable.

(ii) The accelerating fields are located well away from the accelerator walls.

It is worth noting that wave accelerators, for high energy applications, operate in a regime well away from the vacuum space charge limiting current. This is important because it is in this regime that we know how to control the beam. In addition we do not require prohibitively large currents at high electron beam energies.

An interesting view of this type of collective accelerator arises if one examines its similarity to a conventional accelerator. As in the conventional case there are two beams, one to generate the r.f. and the other consisting of the particles being accelerated. The collective regime represents a limiting case of the conventional accelerator in the sense that the two beams overlap or at least are in close proximity to each other. This situation should be compared with the conventional situation in which the beams are well separated from each other. The close proximity of the two beams offers the potential for significant gains in the coupling efficiency between the r.f. generation and the beam acceleration. In his introduction to this conference Lawson[17] pointed out this distinction as he categorized accelerator types. Keefe[16] and Tigner[18] have noted the possibilities for, and desirability of, greater coupling efficiency between the r.f. generation and particle acceleration phases of an accelerator.

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